CBRS Infrastructure and Devices 2018

Abstract: This document is an end-to-end review of the CBRS ecosystem to assess its potential growth, market size, and timing. Infrastructure, SAS connectivity, and core network issues are balanced with handset, CPE, and IoT device availability.

Five different business model scenarios are investigated to fully assess the potential of the CBRS market for mobile operators, cable operators, neutral hosts, and enterprises.

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November 2018

MOBILE EXPERTS

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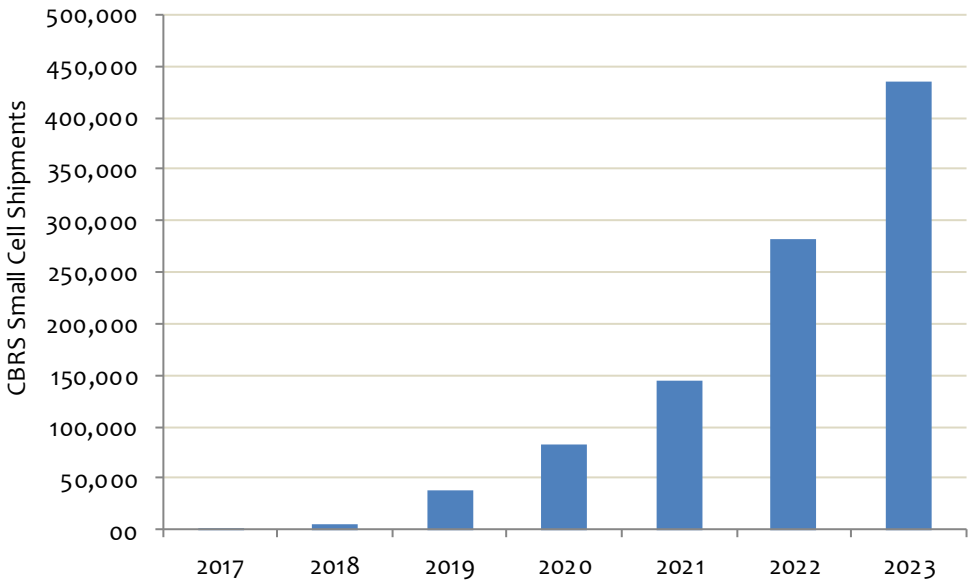
1 EXECUTIVE SUMMARY

What difference a year makes! The CBRS market was somewhat in a holding pattern during the past year as the market waited for the final CBRS rules. On October 24, 2018, the FCC officially released the final CBRS rules that clarified regulatory uncertainty around the 3.5GHz shared spectrum license terms. The rules bolster our confidence in the likely investment by the mobile and cable operators and lessens enthusiasm of the WISPs, enterprises, and other smaller players who looked forward to getting hands-on lower-cost "licensed" spectrum. Now that the rules are final and clear – i.e., license areas based on county and a 10-year term with renewability – the market is ready for a commercial rollout beyond trials.



Source: Mobile Experts

Chart 1: CBRS Small Cell Shipments, 2017-2023

The diversity of CBRS market opportunities in the mobile, cable, and enterprise segments will shift and narrow over time as the revised FCC ruling will encourage some to invest and others to explore "greener pastures" elsewhere. The major mobile and cable operators will be active in deploying CBRS infrastructure to enhance their mobile network capacity for mobile and MVNO offload. Meanwhile, it remains uncertain how active WISPs, enterprises, and neutral host providers will be in deploying CBRS gear for fixed wireless and other indoor applications. The new CBRS rules provide provisions to encourage the secondary market for PAL licenses, and the opportunistic GAA (akin to "unlicensed") use may encourage the smaller players to leverage the spectrum under GAA where PAL is not present. However, technical details around mechanisms to encourage this behavior need to be worked out.

In the near term, the fixed wireless and Private LTE applications will lead the early adoption as some still see opportunities to use the CBRS spectrum under GAA in the near term. Then the outdoor small cell deployment by the mobile operators for carrier aggregation layer for mobile offload will drive the next wave. At the same time, we expect the cable operators to aggressively roll out outdoor and indoor CBRS network to aid in their MVNO businesses.

Major mobile and cable operator investment in CBRS will encourage handset vendors to support the band in the next couple of years. Moreover, the revised emission limits on end-user devices that basically align with 3GPP standard will lessen the friction for CBRS support on smartphones. As the CBRS-enabled smartphones reach a meaningful penetration of the installed base (around 2021-2022), we may see enterprise and neutral host-led indoor deployments to further drive the market.

Overall, we anticipate a rapid growth, with annual shipment of over 400,000 small cells for about $740 million in 2023, and more than 550 billion handsets, CPEs, and IoT devices shipping over the next five years.

2 MARKET DRIVERS

Almost everyone has noticed that competition is heating up in broadband services to American customers. The steady and profitable mobile and cable markets are becoming less predictable as consumer behaviors are changing as more alternatives in video and broadband offerings come to the market. Cable operators and alternative ISPs are beginning to offer wireless services while mobile operators are experimenting with fixed wireless offerings.

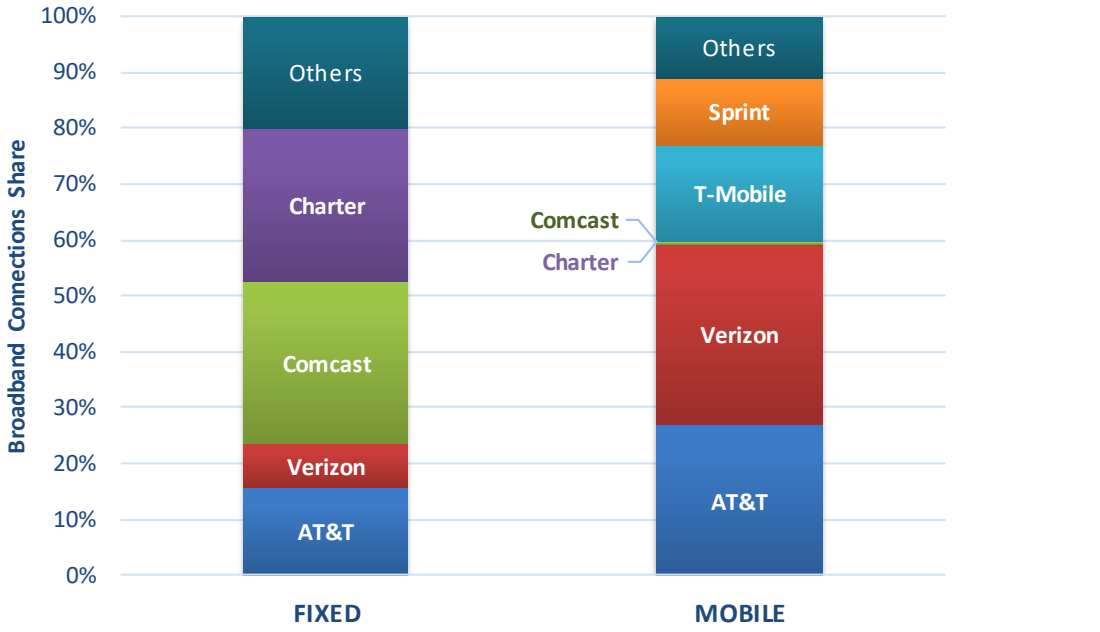
The CBRS band represents a new battleground in this competition between Mobile and Cable. As the technology and product offerings mature, we expect the following business models to prove out whether the new shared CBRS spectrum model will foster new growth or maintain the status quo in the mobile wireless marketplace.

Several new business models can take advantage of the light licensing of CBRS:

1. Fixed Wireless Access: One of the simpler use cases for CBRS involves outdoor infrastructure and fixed broadband service for residential or enterprise customers. For simplicity, we focus on the residential case.
2. Private LTE Networks: Private enterprises can implement their own networks as a way to enhance security, to create IoT connectivity for operations, or to simply save money compared with telecom services.
3. Neutral Host Access: A neutral host can implement a CBRS network instead of a more costly DAS system, to provide coverage in a venue.
4. MNO Capacity Augmentation: Mobile operators can add capacity by adding the CBRS band on top of their existing LTE spectrum.
5. MVNO Mobile Offload: MVNOs such as cable operators can pay exorbitant fees to use a mobile network, so they're highly incentivized to offload traffic to another medium.

Changing Dynamics in Fixed vs Mobile Competition

The mobile and cable operators are beginning to gradually compete more directly as each side fights to retain subscribers that they already have on their core services -- i.e., fixed broadband and video for the cable operators and wireless for the mobile operators. The major cable operators, Comcast and Charter, have already launched mobile service via MVNO (on Verizon's network) and the mobile operators are increasingly posturing towards fixed wireless service offerings where they do not have fixed broadband footprint. While still in early days, Comcast has attracted over 1M wireless subscribers, and Verizon has recently launched 5G fixed wireless service (Verizon 5G Home) in a few markets leveraging a large swath of millimeter wave spectrum on "5G" infrastructure.



Source: Mobile Experts

Figure 1. Fixed vs. Mobile Broadband Connections % Share in the USA as of 3Q'18

As the fixed vs. mobile competition heats up, we expect some of the policies and spectrum and technology choices of the operators to change. Major mobile operators like Verizon have typically stayed away from Wi-Fi due to lack of service quality assurance running services on possibly interference-prone unlicensed spectrum, preferring to focus on LTE on licensed spectrum. On the other side, cable operators relied on Wi-Fi networks within customer premises and sometimes on public outdoor venues and on their cable strands to provide wireless services. As the need for spectrum rises in line with rising mobile traffic growth, both sides are looking for something in between – LTE technology that can run on inexpensive spectrum. With a promise of cheaper spectrum that can be shared among multiple constituents ("Incumbents," PAL licensees, and "unlicensed" GAA users), CBRS promises lower cost-per-bit economics.

Mobile Experts anticipates that the entry of strong cable competitors will open up the mobile broadband market further. For example, while the Hotspot 2.0 did not grow quickly because of lack of support from the giant mobile operators, the mobile operators may be forced to participate if major cable operators drive adoption into enterprise LTE and neutral-host CBRS systems. The introduction of dual-SIM support on recent tier 1 smartphones in the United States is an early indication of loosening of mobile ecosystem by the giant mobile operators. For example, dual-SIM smartphones can theoretically operate on mobile networks of both mobile and cable operators or run on mobile operator's wide area network and operate on private in-building network. We believe that, five years from now, operators will generally be more open to private in-building initiatives, because the

operators won't be investing in indoor systems everywhere. They may be drawn to new business models like neutral hosting to address the in-building wireless challenge in places where direct investment does not make sense.

Fixed Wireless Access

According to a recent FCC report, about 19 million Americans still use DSL, power line, satellite, and other fixed broadband connections that provide less than 10 Mbps downlink speeds because they can't get decent broadband services to their homes.[1] Assuming an average revenue opportunity of $50/month, this segment represents a $11B per year in broadband service revenue that is generally unmet due to the high cost of passing rural and suburban homes with copper, coax, or fiber.

Fixed wireless access (FWA) presents an opportunity to change the "underserved" rural and suburban markets, improving data speed for these 19 million homes. Broad licensed spectrum below 4 GHz is difficult to find, and all available scraps have already been auctioned to the major telecom carriers for LTE operations. But while Verizon and AT&T are chasing big ROI targets in the urban and business markets, the LTE spectrum is essentially idle in rural areas.

Source: Mimosa

Figure 2. A typical Wi-Fi based FWA access point

[1] FCC Internet Access Service report, as of December 31, 2016

The spectrum sharing concept envisioned in CBRS works much better than the traditional exclusive licenses for rural FWA. In a rural area, a local entrepreneur can set up a CBRS network based on fiber and wireless backhaul to a central location, with several subscribers sharing each CBRS access point. Moreover, the opportunistic use of the 3.5GHz spectrum under GAA allows entrepreneurial WISPs to essentially use the band in "unlicensed" manner.

While rural customers are often targeted for FWA service, they are not the only opportunity here. Many urban and suburban customers in the United States are stuck with only a single choice for viable broadband service offerings. With advantaged hybrid-fiber-coaxial plants, cable operators have been taking share away from telcos for some time. While telcos are expanding their fiber footprint, availability of high-speed broadband offerings have been significantly less than cable broadband offerings. With one or two competitive offerings in most markets, the pent-up demand for alternative broadband services is strong but fragmented, based on various levels of service and regional market competition. The FWA opportunity can vary by region and is not well suited to a one-size-fits-all solution. Until major operators divert significant capital dollars towards the FWA market opportunity, it will likely be addressed through many, possibly hundreds of entrepreneurial companies in unserved or underserved areas.

Private LTE Networks

As industrial enterprises increasingly rely on broadband connectivity and leverage more IoT sensors for data gathering and automation, an opportunity for private LTE-based communications networks is starting to diversify and grow. While most enterprises have largely relied upon Wi-Fi for wireless network services, there is a growing recognition that private LTE networks are desirable in use cases where reliable, secure, and predictable connectivity across large geographic footprints (especially outdoors) is critical. As highlighted in last year's report, some of the interesting use cases include:

- Rio Tinto has 15 mines, four shipping terminals, and its own railway in Western Australia. The company uses autonomous mining and transport in a great deal of their network based on a highly developed private LTE network. The Rio Tinto network was launched in August 2013 with four solar-powered trailers that are constantly moved around as mining operations literally change the landscape and terrain around them. Other mining companies such as BHP, Glencore Xtrata, Vale, Freeport McMoRan, and Fortescue are following the lead of Rio Tinto with their own networks and automation. Rio Tinto uses licensed LTE spectrum, and some of the others plan to use 5 GHz LTE-Unlicensed (LTE-U). American mining companies can be expected to use CBRS-based LTE because of high RF power limits and cheap availability of products in the 2019 timeframe.

- Industrial operations are a large potential market. As one example, DSME (Daewoo) and SHI (Samsung) operate automated shipbuilding operations in Korea where LTE

networks control thousands of welding machines for higher quality welding joints. Where unlicensed wireless technologies are replacing Fieldbus or Ethernet wires in some factory settings, larger industrial operations will need LTE for longer range connectivity with low latency and high reliability. GE Digital has partnered with Nokia and Qualcomm in a trial network using the CBRS band, in its Predix lab in California and has postured that it would be investing in Industrial IoT network using CBRS if it can affordably gain PAL license.

- Transportation operations are often discussed for Private LTE networks. Many automated cranes and ground vehicles use RFID technology today, but LTE could give them a boost in range, speed, and flexibility. In addition, LTE could support video operations which would improve safety and oversight of these massive moving structures. CBRS systems can be installed for a locally secured network, without any fees to mobile operators for large data streams such as video.

- Remote operations need automation as well. Shell has introduced a "Sensabot" to conduct routine checks on remote equipment in remote or dangerous locations, dramatically lowering the cost of monitoring oil & gas exploration and drilling sites. One additional aspect of this kind of automation is that often the Oil & Gas industry has locations with potentially explosive gases and other safety hazards for human technicians.

- Point-of-Sale terminals present challenges in security, portable operation, data speed, and reliability. In large venues, portable POS terminals are best implemented on a private network for a secure and predictable connection, every time.

- In addition to all of the above, Public Safety is another key business area for Private LTE infrastructure suppliers. In some cases (such as FirstNet), the network is arguably not a "Private LTE" network since the infrastructure can be made available for the general public's broadband use. However, to the extent that these networks are funded by public safety agencies we count them as a Private LTE network. The growing need for video data in firefighting and law enforcement is now driving much stronger growth in public safety investment for wireless infrastructure, and LTE is quickly moving to the top of the list of "known technologies" that are trusted by key agencies.

While we believe the Private LTE market today is not as big as other analysts claim, it has a good potential to grow if enterprises and neutral host operators are able to access "exclusive" use of spectrum to mitigate interference and contention issues common in some Wi-Fi networks.

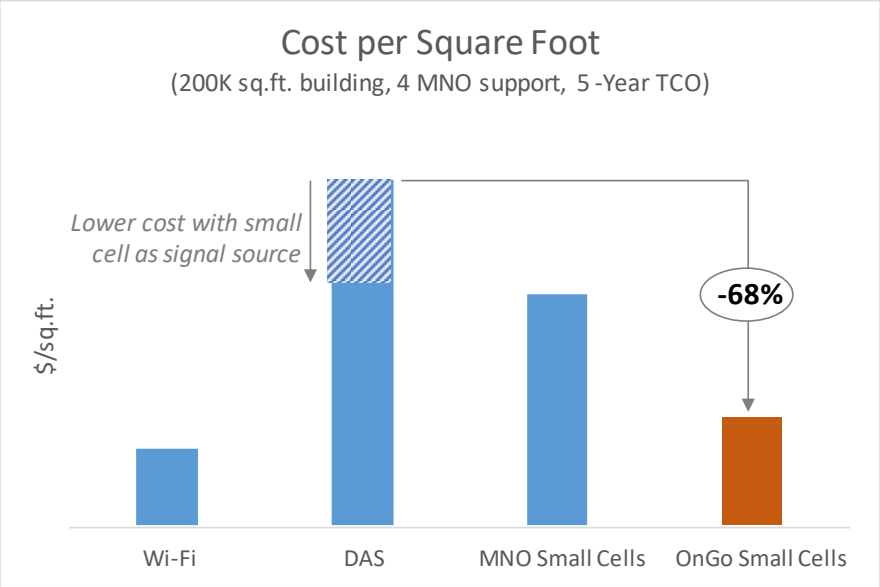
One challenge for Private LTE is the need to coordinate on spectrum with the mobile operators that own exclusive spectrum rights. While a giant player like Rio Tinto has the wherewithal to negotiate a deal with Telstra, most manufacturing plants, retail malls, and

other smaller enterprises would be less inclined to approach a major carrier for a sublease arrangement for licensed spectrum. CBRS can potentially change the dynamics here with cheaper "licensed" PAL spectrum and easy-to-use small cell products which vendors can simply sell to enterprises and neutral host operators. While this model only works in the USA for the CBRS band, the MulteFire equivalent could potentially work on a global scale in the same way.

Enterprise and Neutral Host Networks

Stadiums, large hotels, and airports in the USA are already generally outfitted with DAS systems because the DAS can provide a "neutral" communications platform, meaning that any mobile operator can utilize the coverage for its subscribers. However, the existing DAS infrastructure is limited to 3G in some cases. Continuous upgrades with LTE and higher order MIMO will drive many DAS venues toward very expensive upgrades, as new cabling, amplifiers, and antennas will be needed.

Many smaller buildings in the US market have not been equipped with DAS infrastructure because the overall DAS project costs are prohibitive in these venues -- making an ROI problematic for the operators and too costly for enterprises to pay on their own. Verizon and AT&T feel that small buildings are not worth the effort to coordinate and deploy a DAS. CBRS infrastructure offers a good alternative here. Instead of expensive DAS equipment with high capacity and independent radios for each operator, a CBRS network can function independently of each operator's spectrum, and offer shared access for everyone. Of course, major operators have to be onboard in allowing a neutral host operator to connect CBRS small cell networks to the operators' core networks for seamless roaming and access to operator services.



Source: Mobile Experts

Figure 3. CBRS small cells can offer cost-effective in-building wireless solution

This is not a magic solution… and some operators will not like this approach because of the loss of control over the user experience. In particular, operators that take pride in the quality of their networks do not want to relinquish control to a neutral host company (such as Crown Castle, Extenet, or others). The end user will continue to think that the voice and data services inside the building are offered by the major carrier….so any loss in quality will hurt the carrier's reputation.

So, there are challenges with gaining acceptance and cooperation from the mobile operators, but this solution has the elegance of low-cost shared infrastructure and the ability to provide seamless coverage in millions of buildings across the United States.

One additional challenge for the Neutral Host business model is the dependence on smartphone platforms to adopt CBRS. Today, Apple and Samsung have not confirmed whether their 2019 line up will support CBRS. We expect second-tier smartphone vendors to introduce CBRS support in late 2018 and early 2019, with Samsung products in 2019 and Apple in late 2019 to 2020. This means that the investment in public indoor infrastructure is at least a few years away.

In the Mobile Experts forecast, we count Neutral Host and Enterprise Access networks as a single category, "Enterprise/NH" because it's difficult for us to determine the final business model at this point in time. The system integrators and neutral hosts may take the lead to own the CBRS infrastructure and provide a service, or enterprises may own the infrastructure. Either way, we expect strong involvement from the neutral host providers to make sure that the operator coordination and SAS coordination are done seamlessly.

Moreover, we don't expect the major operators to deal with hundreds or thousands of individual enterprises. They will likely force the market to go the "neutral host" route for enterprise in-building systems.

Mobile Network Capacity Boost

With rising demand and growing mobile traffic, operators are expeditiously employing multiple "tools" in their toolbox to increase network capacity. In certain hotspot locations, they are deploying LAA small cells to aggregate multiple carriers in the unlicensed 5.8 GHz band to opportunistically increase network capacity and user speeds. Despite their efforts to refarm and deploy new licensed spectrum, it looks like the demand is quickly outstripping the network supply.

With the revised CBRS rules with larger license areas and longer-term duration with renewal, the mobile operators' interest in the CBRS band has increased noticeably over the past year. In addition to Verizon and T-Mobile's public announcements, we see AT&T also jumping onto the CBRS "bandwagon" with announced CBRS deployment in 2019. We expect the three major operators to actively pursue PAL licenses in the upcoming auction likely in early 2020.

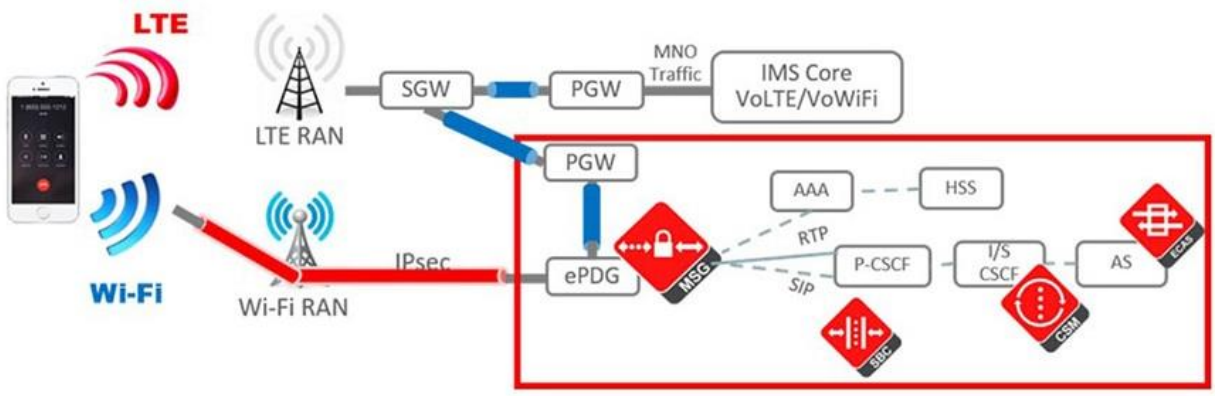
With higher power limits, Mobile Experts expect the mobile operators to leverage the CBRS band in similar manner to LAA. That is, the mobile operators will use their licensed spectrum as a primary carrier and multiple 10MHz CBRS bands as secondary carriers in Carrier Aggregation. But, instead of a much smaller LAA footprint (~50 meters in NLOS reach), CBRS small cells will offer a larger cell coverage (300-400 meters). In essence, we view the mobile operators' CBRS use as a "supersized LAA" deployment on the 3.5GHz spectrum.

Moreover, we believe active mobile operator participation in the evolving CBRS ecosystem will expedite smartphone vendors to support CBRS in the 2019-2020 in concert with operators' CBRS network deployments. The major carriers will not be in a rush to deploy CBRS hardware during 2018, but during 2019 we expect them to begin adoption of CBRS in their outdoor small cell platforms, to be a step ahead of the smartphone products.

MVNO Offload for Cost Reduction

Major cable operators in the US are making their way into the mobile market via the MVNO arrangement that they have negotiated as part of their AWS spectrum sale to Verizon back in 2011. As an MVNO host and an owner of the mobile network, Verizon has the means to check the potential threat of cable operators' mobile services. For cable operators leveraging MVNO, it is all about achieving "owner" economics as fast as possible. Because the mobile LTE data going over the host operator's network is directly charged, the MVNOs are motivated to come up with ways to offload traffic to minimize the "rental" cost of network service fees paid to host mobile operators.

While the cable operators boast about tens of millions of Wi-Fi hotspots to offload traffic, they don't have a complete control over how traffic is diverted and more importantly, the impact on user experience as mobile device roams across LTE and Wi-Fi networks. With CBRS small cells, the network integration and service continuity across the host operator's LTE macro and owned CBRS small cells may afford more seamless user experience than "brute" method of offloading to Wi-Fi. Despite the high pricing, Comcast can use the Verizon network cost-effectively if only 10% of their data is actually passing through Verizon, and 90% of the data is covered by Wi-Fi or CBRS. A few percent drop in traffic going over the Verizon network could mean profitability vs. loss for a cable MVNO.



Source: Oracle

Figure 4. A typical MVNO architecture for cable operators that run a Wi-Fi network

By upgrading their Wi-Fi hotspots to dual-mode CBRS and Wi-Fi hotspots, cable operators can substantially increase their LTE coverage footprint and the reliability of their wireless coverage. Moreover, with higher power limits, CBRS radios may not be required at all of the existing Wi-Fi access points. For urban users within the Comcast footprint, we estimate that more than 95% of the traffic could be covered by the existing AP locations. For the entire suburban and urban Comcast footprint, roughly 80-90% of traffic could be covered. This would reduce Comcast's dependence on Verizon substantially, and possibly result in a profitable mobile service.

Challenges and Unknowns

While the revised CBRS rules have cleared some hurdles like the uncertainty around smartphone support for the band (i.e., mobile operators are invested in the CBRS ecosystem and will force the smartphone vendors to support the CBRS band), they have created

additional hurdles and unknowns related to major investments in the CBRS market, particularly those from smaller players like WISPs, enterprises and neutral host providers.

Mobile Operator Neutral Host Support

One key assumption behind the Neutral Host business model is that mobile operators must allow Core network connectivity so that seamless authentication and access can be enabled over neutral host CBRS small cell network. This is essentially the issue that has limited deployment of Hotspot 2.0. Without enthusiastic support from major operators, the technology never gains critical mass.

When a smartphone user enters a building with a neutral host CBRS network, the ideal case is for the phone to automatically recognize the CBRS network, and send a message to authenticate itself through the CBRS network to the mobile operator's core network. The neutral host or enterprise that owns the CBRS small cell will pass the request on to the core network of the relevant mobile operator, to verify that this is a valid user and that mobile service is allowed via the CBRS RAN. Other policy, charging, QoS measurement, and similar PCRF functions in the core network would also need to be supported.

The interactions with the core network can be brief, and if the local enterprise is sponsoring "free" wireless coverage in the building, the charging and policy functions can be rendered irrelevant. But in all scenarios, a basic SIM authentication function and operator voice communication services must happen at a minimum for the Neutral Host business model to work.

If the mobile operators choose not to support authentication, then third-party neutral host CBRS deployment for public wireless access will grind to a halt. FWA and other private LTE networks can proceed, as companies like Extenet have done with Cal.net and Paladin Wireless using a separate core network. But serving "public" wireless access to all comers will come slowly—like Hotspot 2.0—until the SAS vendors or neutral hosts can aggregate the core connectivity and make it easy to "light up" a building.

Enterprise GAA Use Indoor in a PAL region

In general, the revised CBRS rules favor the major mobile and cable operators with larger PAL license areas and longer term with renewal. For the enterprise neutral host indoor segment to grow quickly, the overall system must provide a mechanism for certain indoor deployments using GAA to take place in urban or suburban region. With the favorable PAL licensing rules, we expect PAL licenses to be hotly contested by the mobile and cable operators, and in some cases by larger enterprise or neutral host operators. Hence, we expect all seven PAL licenses will likely be taken up by the major operators.

In many "sealed" indoor environments (with low-E glasses preventing outdoor signals to penetrate indoor effectively), we believe there are opportunities for enterprising companies

to leverage most of the GAA and even some PAL bands for indoor applications since RF coverage going outside or coming into the venue will be limited. For enterprises to take advantage of this type of "sealed" environments, SAS must be "smart" enough to understand the RF coverage environment inside the buildings to allow "free" use of the band. It is not clear that the current set of standards account for productive utilization of the CBRS band under GAA indoors in a PAL region.

Smartphone Support for CBRS

Smartphone adoption appears to be lagging behind the development of infrastructure. For enterprises and venues to use CBRS for improved access inside the building, then a normal user's phone must have CBRS capability embedded into it. Today, neither Apple nor Samsung have confirmed CBRS support. However, we expect future lineups in 2019 and 2020 will support the CBRS band.

In the smartphone market, there are multiple 3.5 GHz services worldwide that are under consideration, and the CBRS band is one of many possible bands, including new 5G bands in the same C-band spectrum range. The handset community is currently considering alternative approaches to handling multiple 3.5 GHz options (see Section 4 for a more detailed technical review).

In the end, we believe that second-tier handset suppliers including Google/Pixel and a few others will support CBRS with basic capability in 2018. Massive 5G trials in China at 3.5 GHz will drive Huawei, Oppo, Vivo, and Korean handset vendors to support smartphone options. Major flagship phones (Galaxy class and Apple) are not likely to include CBRS capability until the second half of 2019, or possibly 2020.

Based on this timeline, we do not expect to see a large percentage of US subscribers with CBRS capability in their handsets until late 2020 or later. This will set the timeline for many wireless access projects.

3 REGULATORY UPDATE AND IMPLICATIONS

After many years of reassessment, the FCC finally approved the updates to the 2015 CBRS rules concerning PAL license coverage area and licensing term duration along with a few technical factors pertaining to the commercial use of the 3.5 GHz CBRS band. The new Report and Order was just recently approved and released on October 24, 2018.[2] In essence, the updated CBRS rules set larger license coverage area (county-size) and longer license term (10 years with renewal). The final rule changes generally favor larger players (i.e., mobile and cable operators) and change the market dynamics of the different market segments as expected higher PAL spectrum cost and availability will drive investment decisions of the different market players ranging from major mobile and cable operators to WISPs, enterprises, and neutral host providers.

Final FCC Rules

The final FCC rules concerning the CBRS band use settles the long debate among many different stakeholders ranging from mobile operators, cable MSOs, WISPs and enterprises. Like any comprise, no one group seems totally pleased with the outcome, but bigger players including mobile and cable operators seem generally pleased with the outcome compared to the smaller WISPs and enterprises. The larger license area and longer-term duration mostly likely set higher spectrum costs for PAL licenses; thus limiting broad adoption across the different market segments.

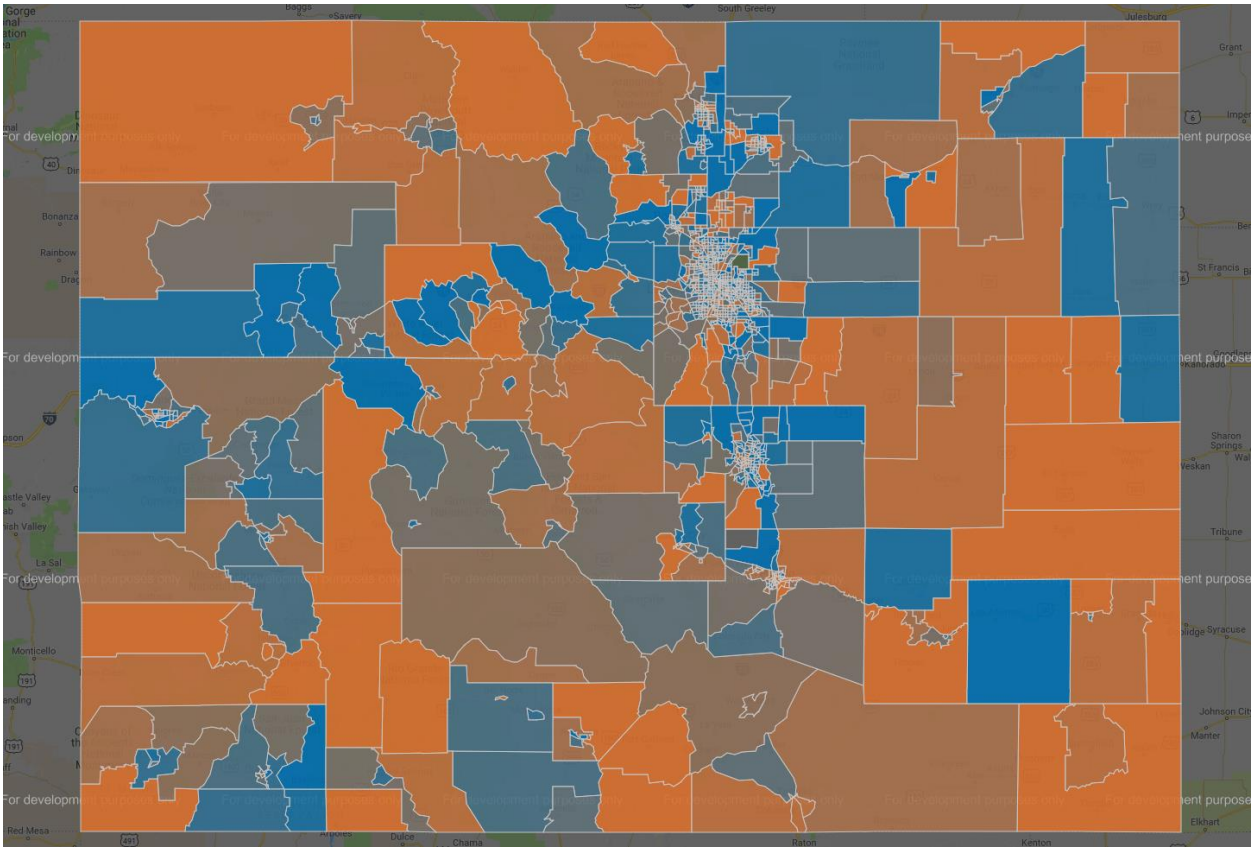
PAL Geographic License Area

One of the key contentions among the different stakeholders large and small has been the PAL license coverage area. The original CBRS rule set the license area based on census tract providing much smaller coverage area, hence granular and lower-cost license areas. While smaller players welcomed the possibility of obtaining cheaper "licensed" spectrum in targeted interest areas, larger players including mobile and cable operators viewed this as too onerous and cumbersome to maintain many licenses to "stitch together" a larger mobile coverage footprint. Moreover, they argued that the small size of census tracts in denser areas create overlapping border edges that increases the possibility of interferences with neighboring PAL licensees.

With over 74,000 census tracts in the USA including Puerto Rico, geographic areas can vary widely depending on population density. For example, below is a map of more than 1,200 census tracts in Colorado. Notice the small census tract areas in the dense urban areas of Denver where a single census tract can encompass a few cities blocks while a census tract in rural areas of the State can encompass a county-wide area. Geographic size and the number

[2] https://docs.fcc.gov/public/attachments/FCC-18-149A1.pdf

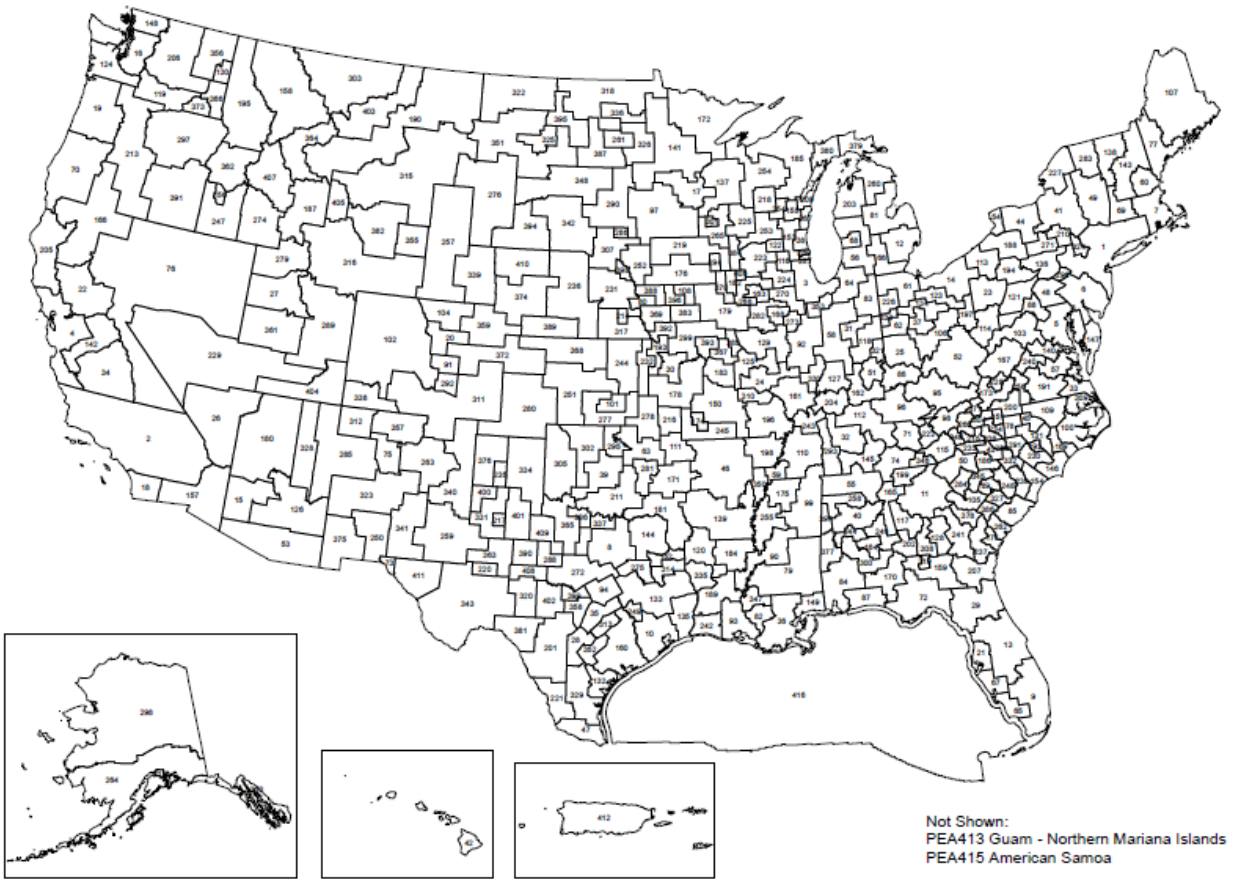
of census tracts can vary widely. For instance, there are over 8,000 census tracts in California. In contrast, Wyoming has only 132 census tract areas in the state.



Source: usboundary.com

Figure 5. 1,249 Census Tracts in the State of Colorado

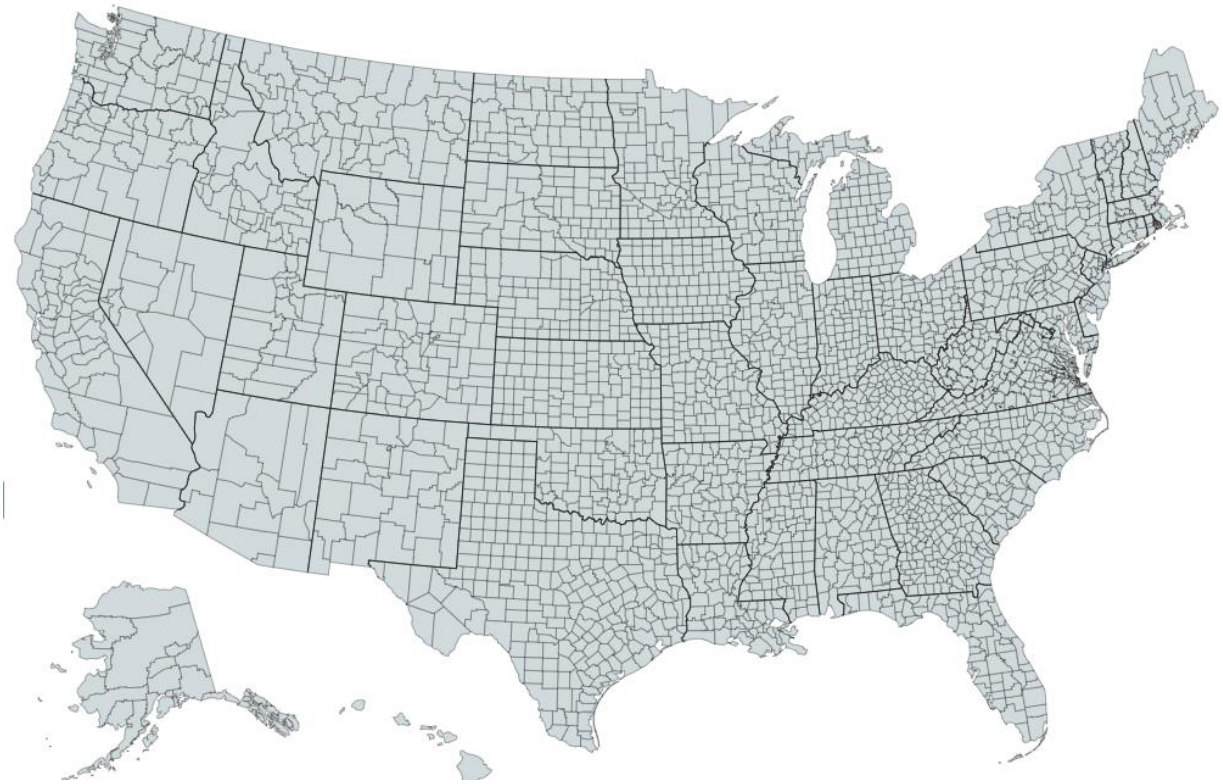
It is no surprise that major mobile operators who have dealt with much larger license areas would lobby for (416) Partial Economic Areas (PEAs) for PAL license area instead of 74,000 census tracts.



Source: FCC

Figure 6. MNO preference for 416 Partial Economic Areas (PEA) as PAL license area

In the end, the FCC settled on the county basis for PAL license area. Reducing the number of PAL licenses from 74,000 census tracts to about 3,000 counties is more palatable compromise for the major operators as well (and FCC auction administrators).



Source: worldatlas.com

Figure 7. New PAL license designation based on more than 3000 counties

PAL Licensing Term Duration

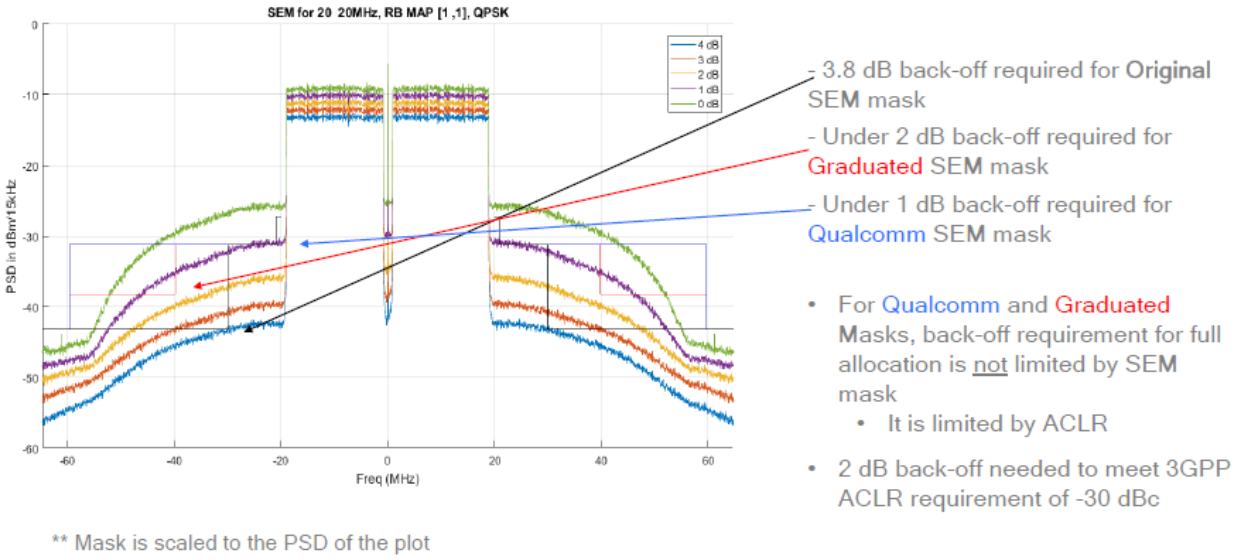
The original CBRS rules called for a three-year term with a one-time renewal extension. For major operators who make capital investment decisions with much longer time horizons viewed the short license term with no renewal expectation as a non-starter. Congruent with its decision to expand the license area to larger county basis, the FCC ruled in favor of a 10-year, renewal term for PAL licensing. The FCC went back to the time-tested licensing terms as a proven framework for major investments in this crucial mid-band spectrum for 5G services.

To ensure productive utilization of the spectrum instead of spectrum "hoarding," the FCC has imposed performance requirement for PAL licensees. At the end of license term, each PAL license must show that it is providing "substantial" service in a license area. For mobile services, the "substantial" service requirement is 50% population coverage. For point-to-point fixed wireless, that requirement is either operate four or more point-to-point links for license areas with 134K population or less, or a minimum number of links equal to the population in a given license area divided by 33.5K. This performance requirement, either directly or under lease arrangement, and opportunistic GAA use of the band may provide opportunities for smaller players to address various market opportunities without heavy PAL

spectrum investment. Moreover, the FCC approval of partitioning and disaggregation of PAL licenses on the secondary market may foster market-based approach for smaller "niche" market opportunities that larger players may not want to pursue.

Emission Limits

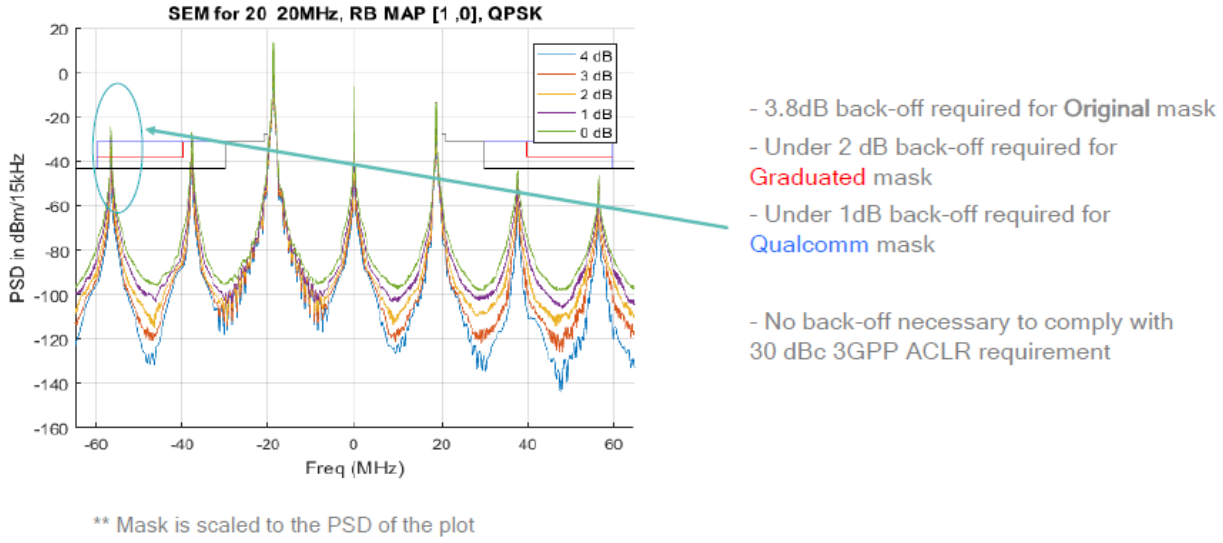
One of the key updates to the revised CBRS rules is the accommodation for some relaxation in the emission mask for uplink transmissions from end-user devices, i.e., smartphones to handle wider channel bandwidth beyond 10 MHz. Under the previous rule, a UE device operating with wider than 10MHz channel would require power reduction to protect operation in adjacent bands. According to Qualcomm simulation results[3] (figures shown below), a revised out-of-band emission limits for UE devices and adjacent channel leakage requirement (ACLR) of -30 dBc, a 3GPP standard, would essentially allow wider than 10MHz channel operation with minimal power reduction.



Source: Qualcomm

Figure 8. Full resource allocation in a 40MHz channel limited by 3GPP ACLR requirement

[3] Qualcomm ex parte on "Additional technical information regarding CBRS emission proposals," March 14, 2018



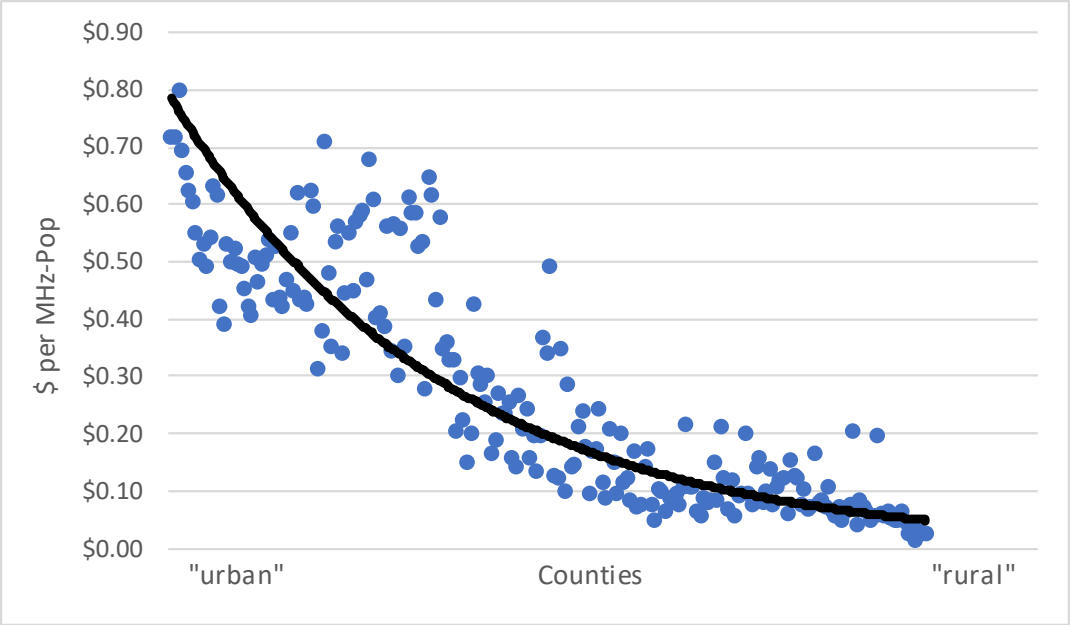
Source: Qualcomm

Figure 9. Low resource allocation in a 40MHz channel limited by proposed emission mask

In other words, CBRS-enabled smartphones sold in the USA don't have to be "non-standard" devices and keeps timing and availability of CBRS-enabled smartphones in concert with mid-band 3.5GHz devices coming to market elsewhere.

PAL Spectrum Cost Estimate

While it is risky to speculate on PAL spectrum costs, we attempt to provide a high-level guideline to assess how much a PAL license may cost based on past market pricing. It should be noted that these are very rough estimates to provide a general framework to think about varying costs associated with types of counties (e.g., urban, suburban, rural). Based on past spectrum auctions, it is reasonable to expect "urban" counties like New York and Los Angeles Counties where top metro markets are located would demand higher pricing. Based on past AWS-3 auction (with over $1 per MHz-Pop on average) and Clearwire spectrum transactions (with over $0.20 per MHz-Pop), we very roughly estimate that CBRS spectrum cost can range from less than $0.02 to $0.70 per MHz-Pop depending on types of markets. Top urban counties like New York and Los Angeles may fetch top end of the price range while rural counties in remote areas demand costs less than $0.01-$0.02 per MHz-Pop.



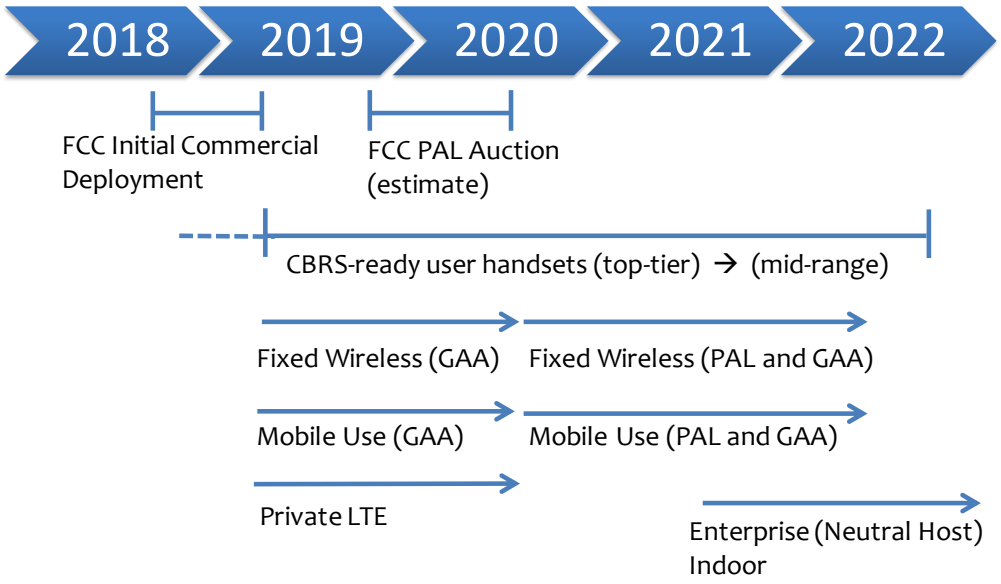
Source: Mobile Experts

Figure 10. CBRS PAL Spectrum Cost Estimates

In terms of absolute dollar figures, the PAL license for Los Angeles could range up to $140M for two 10-Mhz PAL licenses. NY County in comparison could cost about $23M for the same amount of spectrum. The big difference between the two markets is that Los Angeles County has a much larger geographic area covering a lot more population versus significantly smaller geographic footprint of NY County covering about 1/6th of the population. For a rural county such as Sweetwater in Wyoming, two 10MHz PAL licenses could cost less than $50K based on our estimate.

Timeline

Several major SAS providers including Federated Wireless, Google, and Commscope have submitted Initial Commercial Deployment (ICD) proposals to the FCC for real-world testing of the end-to-end system including SAS and CBSDs along with some end user devices. Mobile Experts expects the FCC to complete its review and provide official approval of SAS operations (under GAA) for the initial applications – mostly fixed wireless and Private LTE applications and in some cases, mobile offload use cases. While there is a slight chance that the FCC will soon provide a "green light" for commercial SAS operations, we believe the most likely start date will be first or second quarter of 2019.



Source: Mobile Experts

Figure 11. CBRS Commercialization Timeline

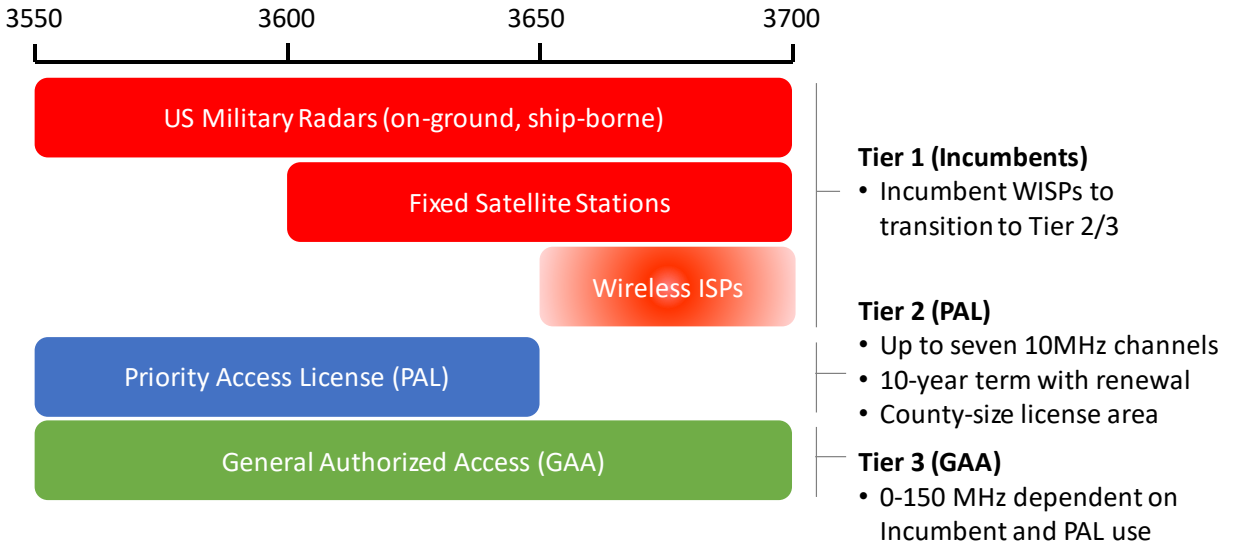
While we believe the major SAS providers are actively rolling out ESC sensors along the coasts for radar detection, we believe this ESC rollout will happen throughout 2019. The initial CBRS infrastructure deployment will largely be inland for fixed wireless and some Private LTE applications, we expect the cable and mobile operators to focus on mobile outdoor deployments. Once the PAL auction is held sometime during late 2019 or early 2020, we expect the CBRS infrastructure rollout to ramp up more quickly. Once the penetration of CBRS handsets reaches a more meaningful share of the installed base (30-40%), we expect enterprise and neutral host indoor deployments to pick up the pace.

4 TECHNOLOGY BACKGROUND

Over the past year, the CBRS ecosystem has made good progress while waiting for the FCC ruling to be finalized. The new technology elements including Spectrum Access System (SAS) and ESC radar sensors continue to be refined through interoperability testing along with CBRS small cell gear. The CBRS Alliance and Wireless Innovation Forum continue to foster ecosystem development and technical standards work. The Wireless Innovation Forum and CBRS Alliance have completed the baseline industry standards, and several CBRS small cell units have been certified by the FCC and several SAS are expected to be certified soon. Once the FCC certifies a few SAS administrators, CBRS commercial operation is expected to start in 2019.

CBRS Basics

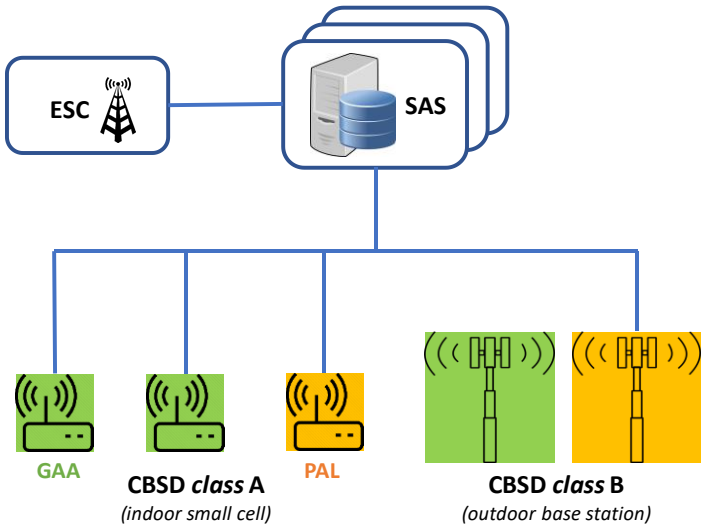
In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with the incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are: *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.



Source: Mobile Experts

Figure 12. CBRS Three-Tier (Shared Spectrum) Licensing Structure

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, environmental sensors known as the *Environmental Sensing Capability* (ESC) are deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 13. CBRS Functional Overview

The CBRS rulemaking defines two classes of base stations: *class A* and *class B*. A class A base station can be thought of as indoor or low power outdoor small cells with a maximum conducted power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise-class" small cells in the marketplace with 250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a class B base station is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS base station can potentially be used for fixed wireless purposes. While indoor and outdoor base stations can be assigned to either GAA or PAL, we expect to see more GAA deployments inland until ESC certification and PAL auctions get finalized.

While several SAS administrators have been conditionally approved by the FCC, Federated Wireless, Google, and Commscope seem most active based on their partnerships with some

major operators and vendors. Federated Wireless has submitted Initial Commercial Deployment (ICD) plan to the FCC touting over 15,000 sites. Meanwhile, Google has been quietly working with some key players to exercise its core SAS offering. In addition, it has partnered with Commscope to co-develop ESC infrastructure. Commscope has partnered with Samsung to leverage its SAS solution along with Samsung fixed wireless radios for AT&T's planned fixed wireless service launch in second half of 2019.

Small Cells

With two distinct CBSD categories, CBRS base stations coming to the market will include both Outdoor and Indoor small cells. Mobile Experts defines small cells as self-contained radio nodes which include all Layer1-3 baseband processing for licensed mobile communications. Small cells use a highly integrated RAN structure with baseband and radio functionalities collapsed in an integrated design. One variation on this theme is small cell units that are broken into two physical boxes (such as Spidercloud enterprise small cells and Ericsson Radio Dot), where some Layer 1/Layer 2 baseband processing is executed in the radio unit and the rest of Layer 2/Layer 3 processing is done in a controller box for multiple radio units. Where this split is achieved locally within the building, we still consider the unit to be a "small cell."

Source: Ericsson, Nokia, Ruckus, Sercomm

Figure 14. Examples of Outdoor and Indoor CBRS small cells certified by the FCC

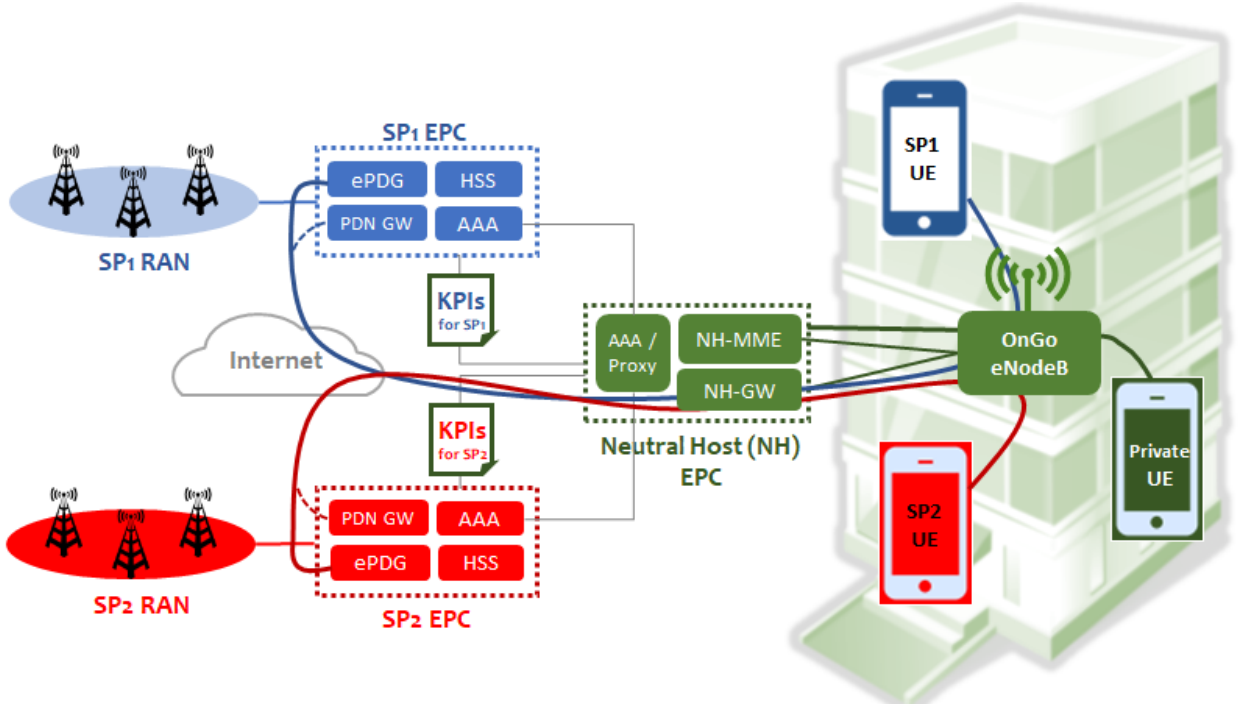
Above depicts some small cell gear that has already been certified by the FCC for CBRS use. While only four vendors have been approved thus far, including Ericsson, Nokia, Ruckus, and Sercomm, we expect several more to be certified in the next few months as the pace of CBRS deployment picks up in 2019. It should be noted that most vendors have both indoor and outdoor units available for network deployment.

Core Network Connectivity

Operators don't want to deal with setting up EPC connections to every new building and every neutral host that enters this market. At the same time, enterprises and some neutral hosts don't have the right contacts to coordinate with all of the operators' core networks. So, there is a new opportunity here for a Neutral Host Network operator to take a "clearing house" role in authenticating and setting policy for the operators and possibly running in-building wireless network on behalf of enterprises.

Here, connection to the Core Networks is key because each handset that enters the building must be authenticated in order to access mobile network services. In addition to authentication and authorization, other policy and control functions specified by the operators must be enforced to in order to ensure consistent user experience. Individual connections to each service provider's EPC would be duplicative and inefficient. We expect this market to quickly move to a few key aggregators, possibly led by some of the leading SAS providers or neutral host wireless infrastructure providers like the tower companies.

Managed services through a neutral host network (NHN) provider requires integration of core networks between the NHN and multiple network operators as shown below. The interworking between NHN and multiple operators can leverage the WLAN internetworking architecture as defined in 3GPP. A mobile device can use ePDG to gain access to an operator's IP services, including voice services over IMS. The service continuity is maintained between NHN and an operator network, and local IP services (e.g., enterprise PBX) can be provided through local breakout at the neutral host network. Another key aspect of the NHN core network is to provide key performing indicators (KPIs) or charging metrics to operator's core network through NHN EPC. Since the NHN in this case needs to meet the CBRS governing rules, the NHN core also needs to interface with SAS for dynamic channel assignments through the CBRS Gateway as necessary.



Source: Mobile Experts

Figure 15. Core network connectivity between a Neutral Host and Mobile operators

Roaming onto Neutral Host Network (NHN) leverages the same cellular roaming principles and procedures as roaming onto another operator's network. A UE device first discovers a CBRS network by scanning the CBRS frequency band for a network broadcasting the CBRS Shared Home Network Identifier (HNI)[4]. The device then determines if the network supports Neutral Hosting and reads the list of Participating Service Provider IDs (PSP-IDs). It should be noted that if a service provider has a commercial roaming agreement with the NHN operator, then the neutral host network would be broadcasting the participating service provider's network identifier PLMN-ID[5] in its list of PSP-IDs. If the device is pre-provisioned to access any of the listed PSP-IDs, it would then begin to attach and authenticate to the NHN network to roam. As a part of the neutral host commercial arrangement, the service provider is responsible for pre-provisioning one or more corresponding CBRS identifiers, CBRS-I onto device SIM so that its "NHN-capable" devices can discover and attach to allowed neutral host networks. It should be noted that the CBRS Alliance in close collaboration with ATIS, which manages IMSI[6] resources in the United States, assign IMSI identifiers for CBRS use case.

[4] A Shared HNI is shared among multiple operators in the CBRS spectrum. NHN operators can use a PLMN-ID assigned for shared CBRS use or apply for own PLMN-ID as CBRS-I.

[5] PLMN-ID (Public Land Mobile Network Identifier) is a unique identification of a service provider, comprised of MCC (mobile country code) + MNC (mobile network code).

[6] IMSI (International Mobile Subscriber ID) is a 15-digit unique identifier for each mobile user device. For CBRS/OnGo use case, the 9-digit mobile subscriber ID is further partitioned into 4-digit IMSI Block Number(IBN) and 5-digit User Identification Number (UIN) resulting in 10,000 blocks of 100,000 IMSI's.

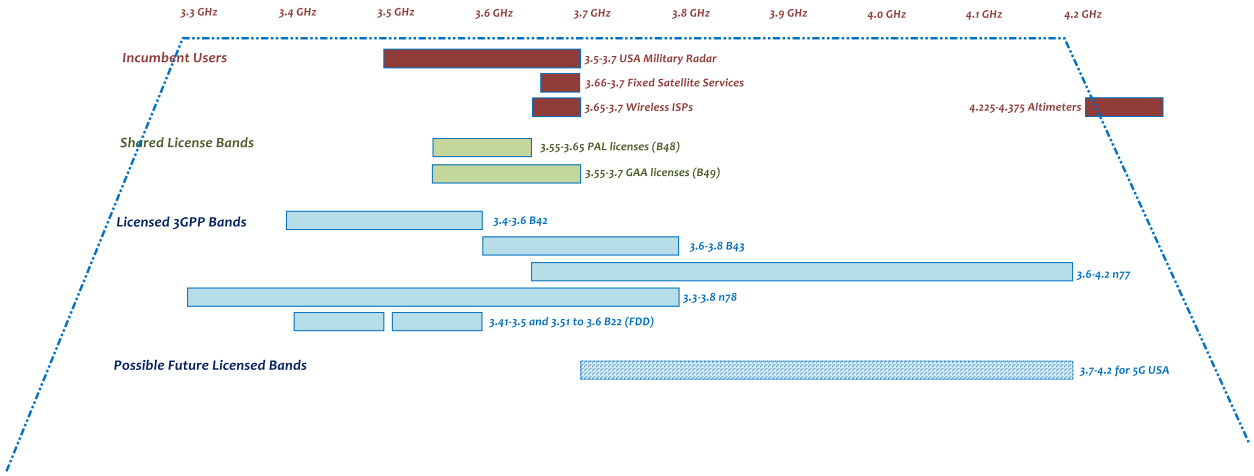
Once a UE device has selected or roamed onto an NHN, the data connection between NHN and the mobile operator can operate in either "trusted" or "untrusted" mode. In "trusted" mode, an NH-GW connection to the participating mobile operator's PDN-GW uses the standard 3GPP interface. In "untrusted" mode, a NH-GW connection between user device and mobile operator network services is handled through secure IPsec tunnel via the Internet to mobile operator's ePDG which manages interworking between the operator's EPC and untrusted non-3GPP networks such as Wi-Fi or neutral host CBRS network.

User Devices

It's important to keep in mind that the USA is not a big enough market to drive instant acceptance of a new feature such as CBRS into global smartphone platforms. Apple and Samsung's Galaxy team are currently considering how to implement the 3.5 GHz band into handsets, and their choices are complicated by a variety of LTE, 5G, and CBRS plans that range from 3.3 GHz to 4.2 GHz.

There are two choices for implementation of filters for CBRS, LTE, and 5G services between 3.3 and 4.2 GHz.

1. The obvious first choice for simplicity is to use a single bandpass filter, covering the entire band from 3.3 to 4.2 GHz.



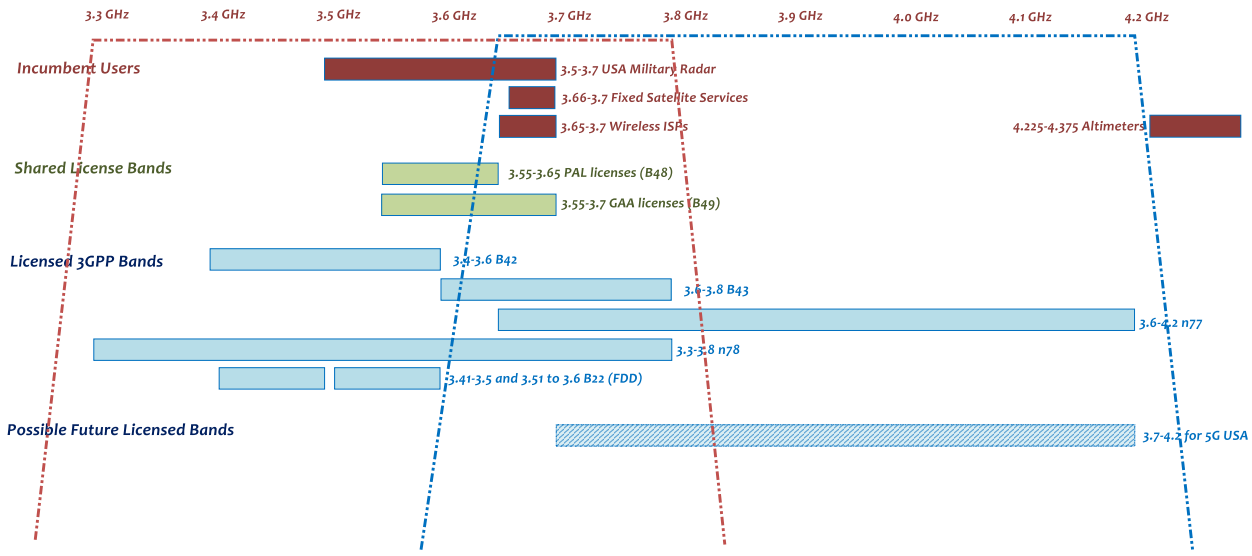
Source: Mobile Experts

Figure 16. A single-filter implementation at 3.3 to 4.2 GHz

This would be a fairly low-cost approach due to the limited number of filter/PA combinations involved. However, the drawbacks would include poor PA efficiency due to the wideband covered (24% fractional bandwidth), and shallow rejection skirts

due to the wide bandwidth of the filter. Rejection of the altimeter and adjacent radar systems would be weak.

2. A second choice involves splitting the 3.3-4.2 GHz band into two slices, such as 3.3-3.8 GHz (known as *n78* in 5G band designation in 3GPP) and for other apps at 3.6-4.2 GHz. In this arrangement, each regional use case would be covered by one of the filters. It should be noted that the most likely implementation would be as a single Complete Front End (aka PAMiD) module that covers multiple bands and multiple PA paths, so that each of these two filters would have a narrowband power amplifier supporting it, for higher efficiency performance.



Source: Mobile Experts

Figure 17. A dual-filter implementation at 3.3 to 4.2 GHz

Overall, we believe that the second option is preferable, which provides better protection from out-of-band radar and altimeter systems and higher efficiency, with only a small increase in cost.

In terms of timing, we currently see implementation of 3GPP Band 42 filters in a few smartphones in Japan (covering up to 3600 MHz), and there's some development underway with second-tier handset manufacturers for handsets to cover 3550-3700 MHz for the 2018-2019 early deployments. We believe that Apple and Samsung will introduce this band in 2020, after PAL licenses are issued.

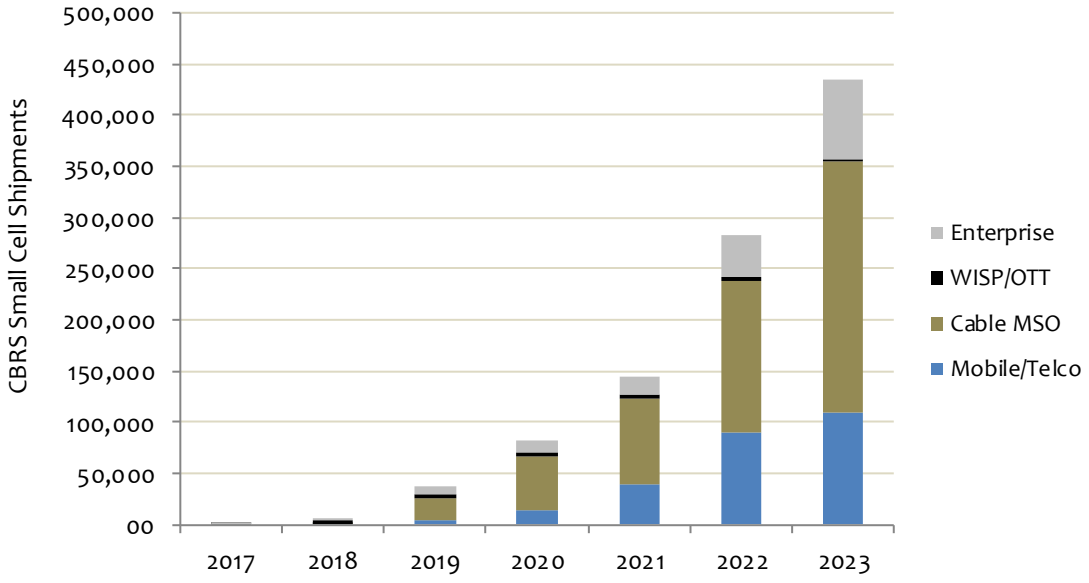
In 2019, we expect Google/Pixel, LG, and a few other second-tier handset vendors to have the band support available. We predict that major global smartphone platforms will start with Samsung's regional smartphones for the US market, followed by a worldwide Galaxy

class handset in 2019. We estimate that Apple is not likely to support the full CBRS band until 2020. In summary, we don't expect the penetration of CBRS in American handsets to reach critical mass of 30% or higher until 2021 or later.

5 CBRS OUTLOOK

The CBRS market ramp-up in the second half of 2018 did not materialize as we had initially forecasted in the last year's report. A key assumption driving the last year's forecast was that the original CBRS rules based on census tract coverage areas and shorter licensing term duration would largely remain intact. More importantly, we had expected the FCC to allow commercial operation under GAA in 2018 while it worked out PAL spectrum auction sometime in 2019. Of course, this did not happen. The FCC has been deliberate in reassessing the CBRS rules and cautious in rolling out commercial services under the new shared spectrum regime.

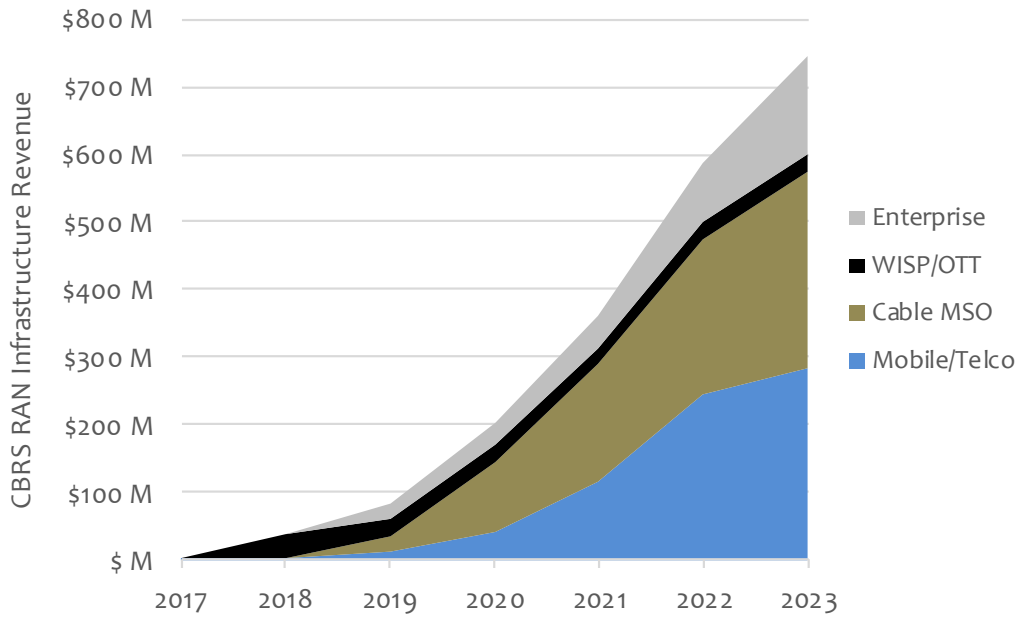
With the recent FCC rulemaking based on county-size coverage areas and a ten-year licensing term with renewal and expected approval of Initial Commercial Deployments (ICDs) filed with the FCC, the market ramp will start in the first half of 2019. While the market ramp has been delayed somewhat from last year's forecast, the underlying market demand has not subsided. Mobile Experts forecasts a three-digit percentage growth in CBRS radio infrastructure shipments and revenue over the forecast period from 2017 to 2023. While multiple service provider groups and large enterprises will deploy CBRS radio infrastructure, with the updated CBRS rules, larger mobile and cable operators will drive most of the infrastructure investment. With expected higher spectrum costs associated with larger coverage areas and longer licensing term duration, the participation from regional WISPs and smaller enterprises will be limited as these smaller players will find the updated CBRS rules generally more onerous.



Source: Mobile Experts

Chart 2: CBRS Small Cell Shipments, by business model, 2017-2023

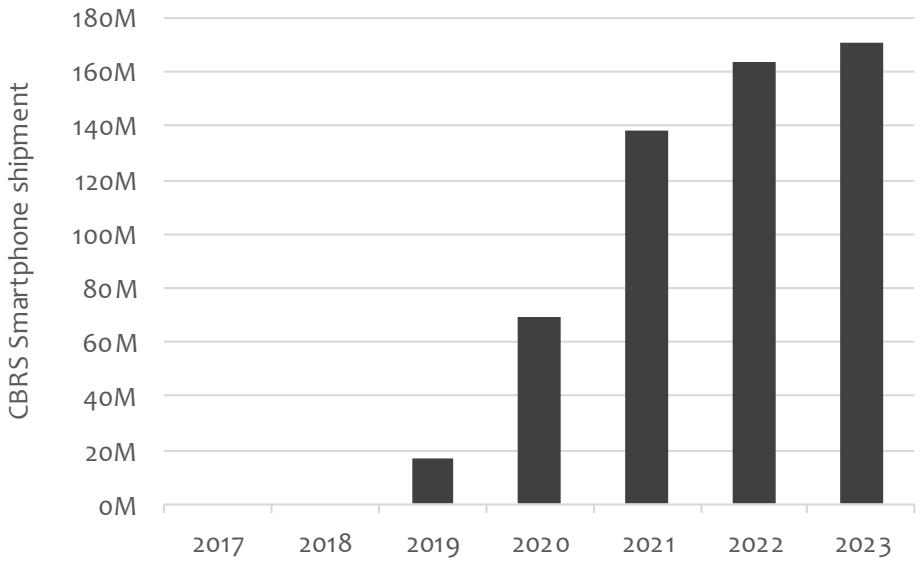
Revenue for CBRS infrastructure will grow quickly. The early fixed wireless implementation by WISPs and some Private LTE applications from larger enterprises will drive the initial deployments in 2018-2019. In anticipation of PAL spectrum auction possibly in late 2019 and most likely early 2020, the mobile and cable operators will start deployment throughout 2019. Mobile Experts expects the cable operators to be most active in the early years as they look to CBRS network as a cost reduction strategy for their MVNO offering. While more deliberate in their approach to deploying CBRS, the mobile operators will ramp up their CBRS infrastructure deployment as another means to increase network capacity. We will result in a lot of outdoor access point deployment, with high ASPs in the first few years. We expect revenue to reach over $700M for CBRS RAN infrastructure within five years.



Source: Mobile Experts

Chart 3: CBRS Small Cell Revenue, by business model, 2017-2023

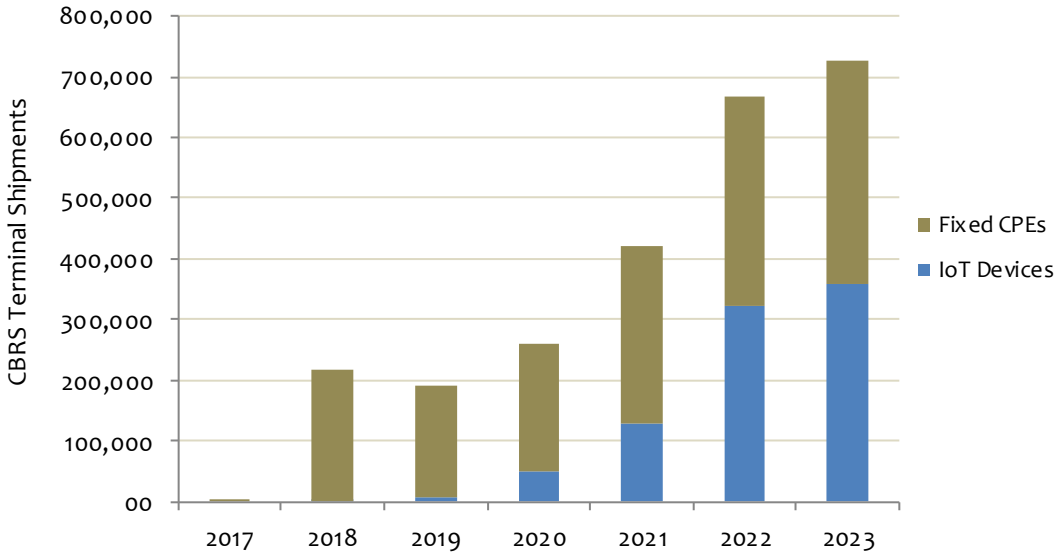
Mobile Experts envisions three different types of terminals for CBRS use. Smartphones, of course, will dominate with mobile application driving a major portion of CBRS infrastructure investment by both mobile and cable operators. They will be modified to work on the CBRS band for general LTE access. While we believe many tier 1 smartphones coming to the market in late 2018 are capable of supporting the CBRS band, they won't be officially certified for CBRS band 48 until FCC approves CBRS radio infrastructure first. We expect CBRS-enabled smartphones to come to the U.S. market in second half 2019. By 2021-2022, we expect majority of high-end and mid-tier smartphones to support this band, with about 150M smartphones sold during that period. In other words, practically every LTE handsets sold in the USA will include CBRS by 2023.



Source: Mobile Experts

Chart 4: CBRS Smartphone Shipments in the USA, 2017-2023

While far fewer in unit shipments, non-handset terminals will also grow quickly. IoT devices will be used in Private LTE applications, growing to hundreds of thousands of units per year by 2022. In addition, CBRS fixed wireless access will involve hundreds of thousands of CPEs customer premise equipment (CPEs) to enable fixed wireless broadband access. The initial terminal deployment will be dominated by fixed wireless CPEs as WISPs leverage the "incumbent" 3.65 – 3.7 GHz band for fixed wireless access until that band falls under the CBRS rules in the next couple of years. IoT and smartphone terminals will become a more significant portion as Private LTE and general mobile applications become more widely adopted in 2020 and beyond.

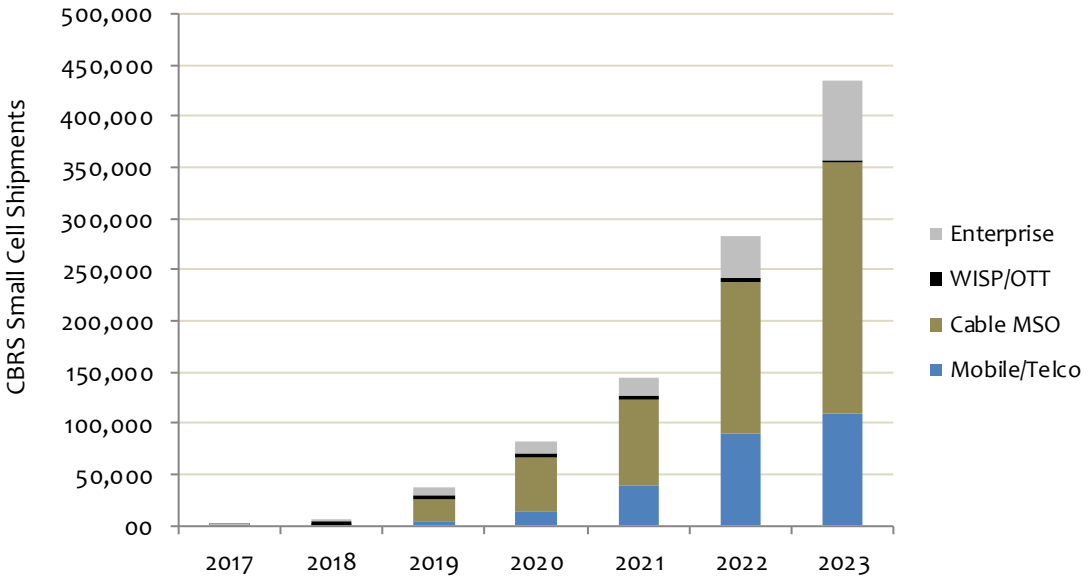


Source: Mobile Experts

Chart 5: CBRS CPE and IoT Device Shipments, 2017-2023

CBRS RAN Equipment Forecast

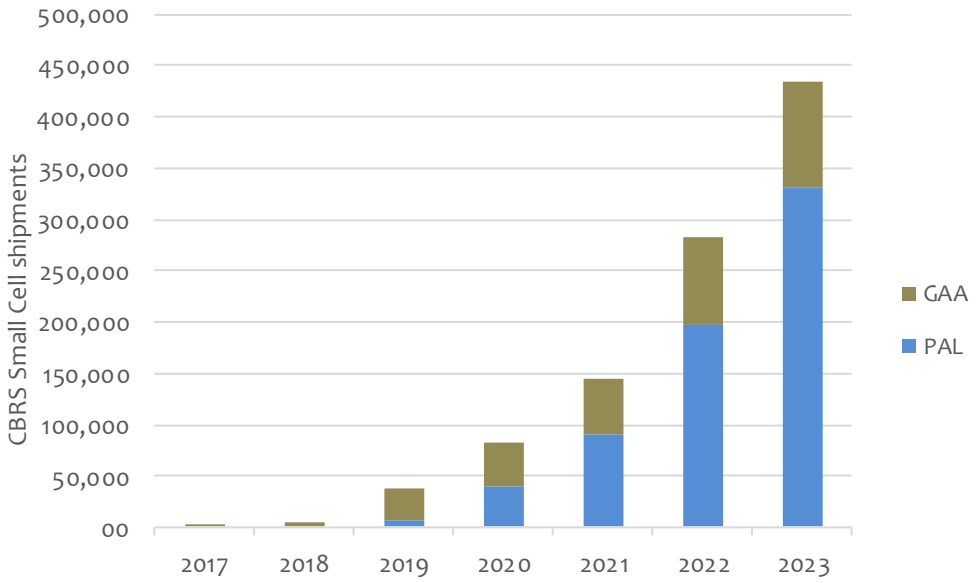
A tepid CBRS radio infrastructure shipments in 2018 due to the delay in regulatory approval process is now expected to improve heading into 2019. The initial deployments will be led by WISPs for fixed wireless access and enterprise Private LTE applications. While mobile and cable operators may also contribute to FWA use, we expect the contribution to be relatively minimal. As the PAL spectrum use becomes more clear heading into 2020, the cable operators are expected to be aggressive in rolling out CBRS radio infrastructure to aid in their MVNO businesses. As the penetration of CBRS-enabled smartphones becomes more significant in 2021-2022, the enterprise CBRS infrastructure deployment is likely be ramp up. By 2023, Mobile Experts forecasts the cable operators to deploy over 57% of all CBRS radio infrastructure (a meaningful portion of this coming from CBRS-enabled wireless CPEs in addition to traditional CBRS small cells). Meanwhile, the mobile operators will deploy over 25% of all CBRS radio infrastructure mostly in outdoor units to enhance capacity. Moreover, large "tech-savvy" enterprises and some neutral host providers are also likely to deploy about 16% of all CBRS radios in 2023 to take advantage of new CBRS spectrum band for enterprise applications that require greater service quality. Lastly, the WISPs that had hoped for greater share of "licensed" portion of the CBRS band will opportunistically deploy CBRS infrastructure to enhance their FWA services and will represent less than 1% of CBRS infrastructure deployment in 2023.



Source: Mobile Experts

Chart 6: CBRS Small Cell Shipment Forecast by Operator Type, 2017-2023

Major operators' preference for licensed spectrum is not a surprise, of course, since the exclusive use provides interference protection and ensures quality of service. As such, the mobile and cable operators have a strong preference for use of the PAL licenses, because the PAL licensing arrangement essentially provides "licensed" spectrum use for most areas of the country most of the time. In contrast, the GAA use brings the unknown quality associated with the "unlicensed" use. With the updated CBRS rules favoring "larger" players like the mobile and cable operators with county-size coverage areas and a ten-year term with renewability, the CBRS radio infrastructure deployment using PAL will dominate over the GAA use. While WISPs in rural areas and certain Private LTE networks will use GAA where the probability of incumbent or PAL use is minimal, they will be fewer relative to the majority of CBRS infrastructure leveraging PAL.

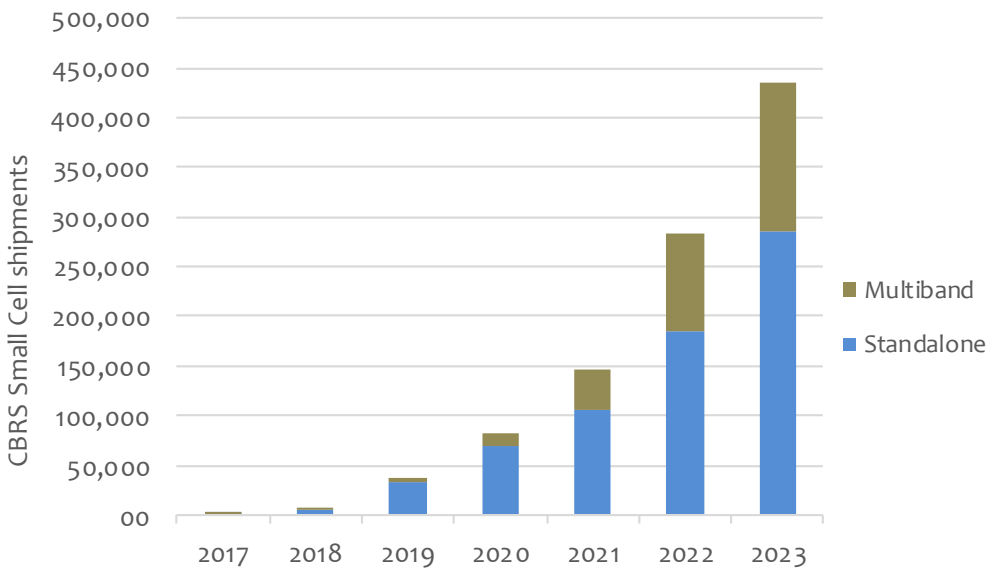


Source: Mobile Experts

Chart 7: CBRS Small Cell Shipment Forecast by License Type, 2017-2023

Mobile Experts expects the mobile operators to deploy CBRS multiband small cells, meaning that CBRS will be used along with a licensed LTE band with Carrier Aggregation. In this way, the operators will be able to leverage the shared CBRS band in LAA fashion - i.e., aggregate carriers across both shared and licensed spectrum bands to increase capacity and enhance user throughput. Cable operators and Private LTE, on the other hand, will use control channels in the CBRS band, with the possibility of Carrier Aggregation/LAA on the 5GHz unlicensed band. For simplicity, we count the Cable MSO deployments as "Standalone" despite this possibility.

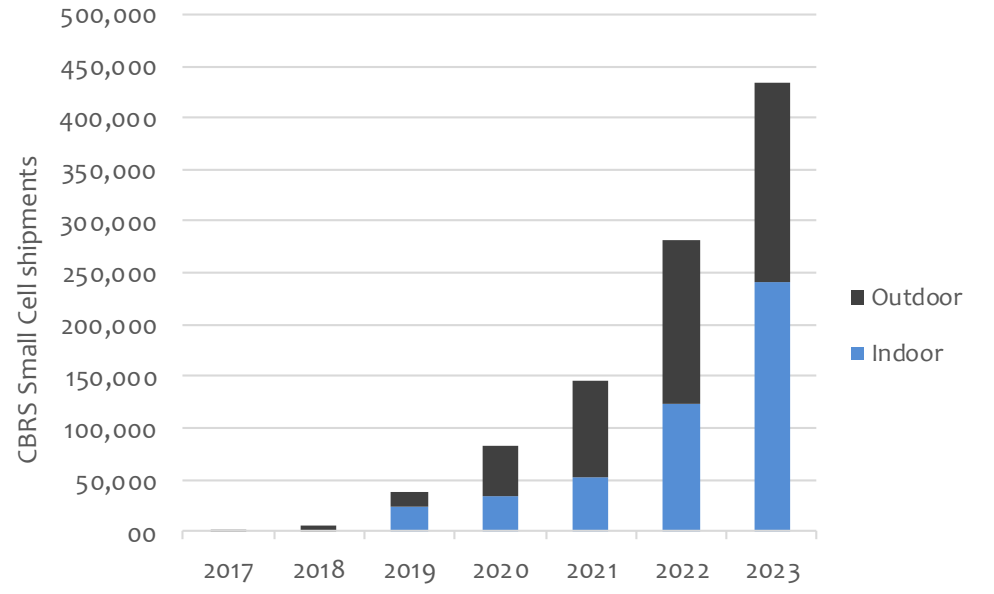
In the near term, Mobile Experts forecasts the cable operators to be more aggressive in both outdoor and indoor deployments to improve "owner economics" of their MVNO businesses, so the "Standalone" category dominates the picture. By the end of the forecast period, Mobile Experts forecasts the mobile operators to deploy the majority of all CBRS radios as multiband small cells for mobile use. Meanwhile, the cable operators are expected to deploy the majority of their CBRS radios as standalone small cells.



Source: Mobile Experts

Chart 8: CBRS Small Cell Shipment Forecast by Multiband vs Standalone, 2017-2023

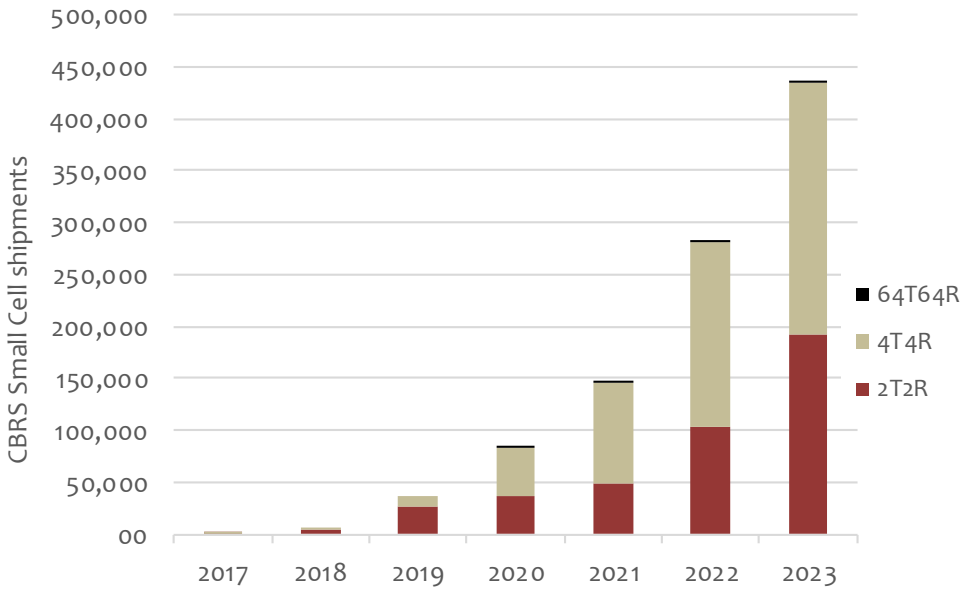
Both mobile and cable operators are likely to make heavy use of outdoor CBRS access points. In addition, the cable operators will aggressively leverage their advantaged fixed broadband footprint to deploy CBRS indoor units to expand their "mobile network" capacity. As Private LTE systems ramp up in the enterprise market in 2021-2023 timeframe, we will see a lot more indoor CBRS small cells coming into the market as well.



Source: Mobile Experts

Chart 9: CBRS Small Cell Shipment Forecast by Indoor vs Outdoor, 2017-2023

In the early days of the market, CBRS is considered a coverage solution, so 2x2 MIMO is currently designed into a lot of the early small cell products. Over time, we expect that 4x4 MIMO will be used, especially as 5G handsets emerge with 4x4 capability in the 3.5 GHz band. 5G operation in that band will drive 4x4 hardware implementation, so we expect smartphones to support CBRS with 4x4 as well. The clear trend over the longer term will be toward 4x4 small cell infrastructure. Also, some 64T64R units may be leveraged to enhance coverage and capacity in fixed wireless use. In context of the overall units, these high-end massive MIMO units will be significantly less.



Source: Mobile Experts

Chart 10: CBRS Small Cell Shipment Forecast by MIMO order, 2017-2023

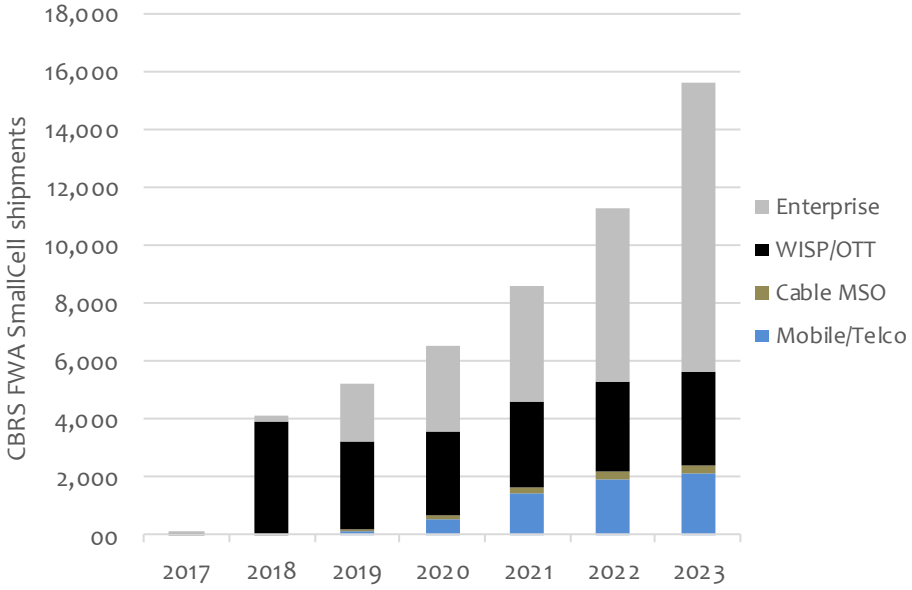
CBRS Fixed Wireless Access Forecast

The CBRS spectrum is a great fit for the Fixed Wireless Access application, with long range, good penetration of foliage, and inexpensive access to spectrum, especially in rural areas. Early adopters are already moving forward, despite the lack of maturity in the spectrum and solutions with a promise of cost-effective "licensed" spectrum. Mobile Experts estimates that WISPs have an installed base of over 30,000 Wi-Fi or WiMAX-based FWA sites, and based on steady replacement of these legacy solutions with superior CBRS radios, we have observed early surge of deployments in the very near term. With the updated CBRS rules that favor bigger players with higher expected cost of the PAL licenses, only a handful of larger WISPs may participate in the upcoming PAL auction. While there is a hope that rural WISPs will continue invest in the CBRS radios using GAA, there is a less certainty and probability of this happening long term. Instead of a rapid adoption of CBRS radios by the

WISPs for fixed wireless, we now forecast a moderate uptake characterized by opportunistic deployments in rural areas under GAA.

With the AT&T's announcement of fixed wireless deployment using CBRS to meet its CAF requirement of providing 10/1 Mbps service in rural areas, we forecast a moderate FWA uptake by the mobile operators. Mobile Experts believes that the mobile operators' primary use of CBRS radios will be focused towards mobile use to increase network capacity.

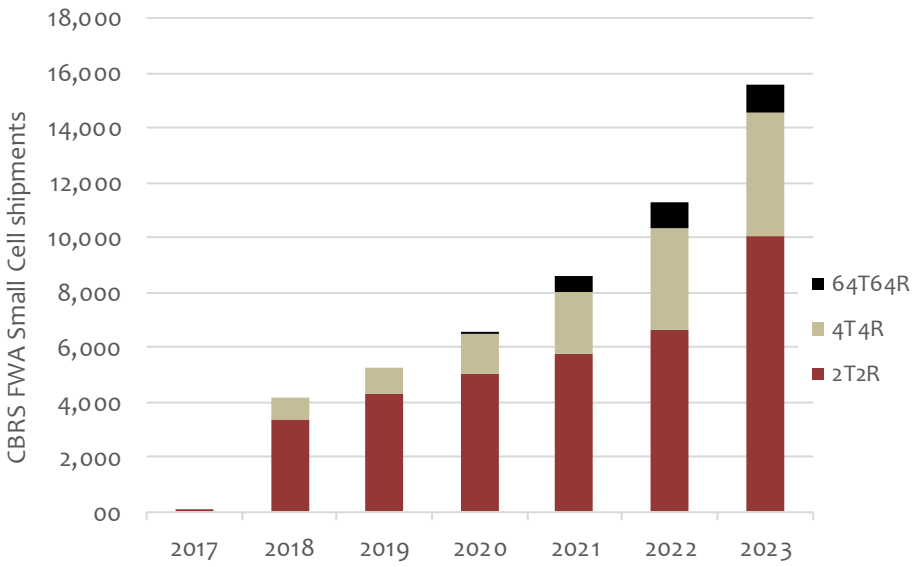
Private LTE systems for fixed access can include security cameras and other fixed assets. While we generally view this type of deployment represents a large market opportunity, the updated CBRS rule changes favoring larger players in lieu of smaller enterprise players diminishes the incentives for Private LTE networks especially for the outdoor context. We expect fixed wireless access in the context of enterprise Private LTE applications to be niche – at least for the CBRS use.



Source: Mobile Experts

Chart 11: CBRS FWA shipment forecast, by operator type, 2017-2023

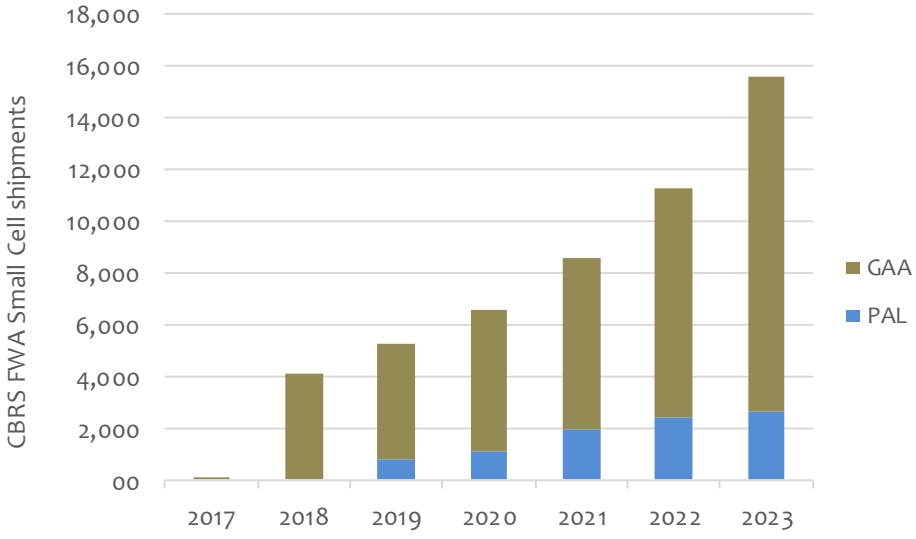
Most fixed wireless CBRS small cells will use 2x2 MIMO at first, but we expect these to quickly migrate to 4x4 MIMO because the CPEs are not constrained by antenna size or similar considerations. In some instances, we expect massive MIMO configurations like 64T64R may be applied in fixed wireless deployments in denser environments to increase network capacity, and in certain cases, the range of small cell coverage.



Source: Mobile Experts

Chart 12: CBRS FWA shipment forecast, by MIMO order, 2017-2023

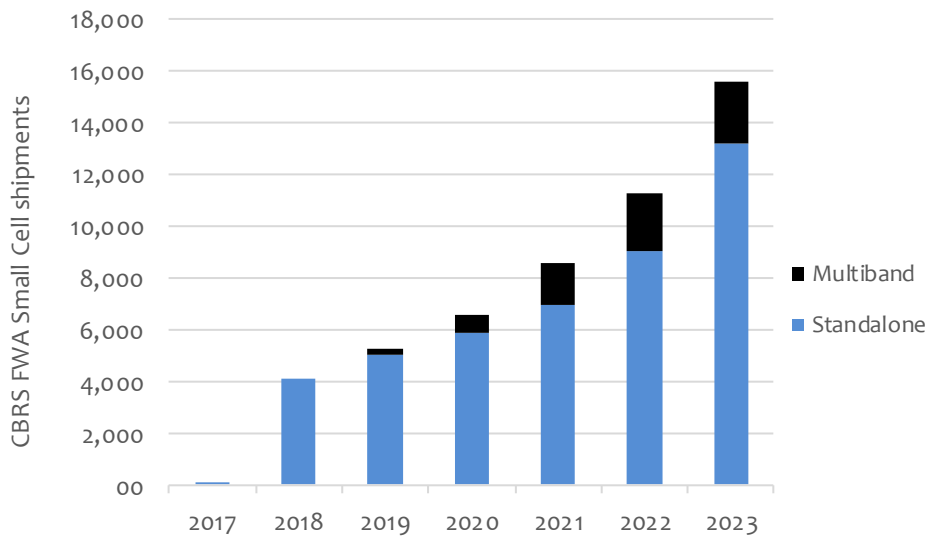
With the updated CBRS rules that extend PAL licensing to ten years with renewal, we expect only larger WISPs may be inclined to participate in the PAL auction. In most cases, we believe rural WISPs to deploy CBRS infrastructure and run their services under GAA with a hope that PAL licensees won't actually deploy radio infrastructure in their markets.



Source: Mobile Experts

Chart 13: CBRS FWA shipment forecast, by GAA vs PAL, 2017-2023

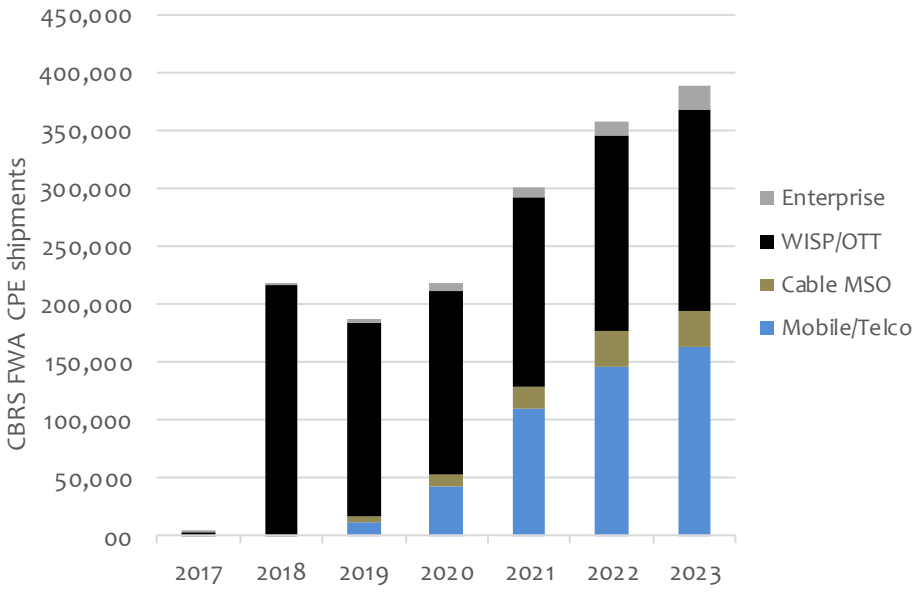
Most FWA deployments will be stand-alone for WISPs and Private LTE deployment. Mobile operators deploying LTE for fixed wireless access may use some multi-band units but we expect simple solutions to dominate this market.



Source: Mobile Experts

Chart 14: CBRS FWA shipment forecast, Standalone and Multi-band, 2017-2023

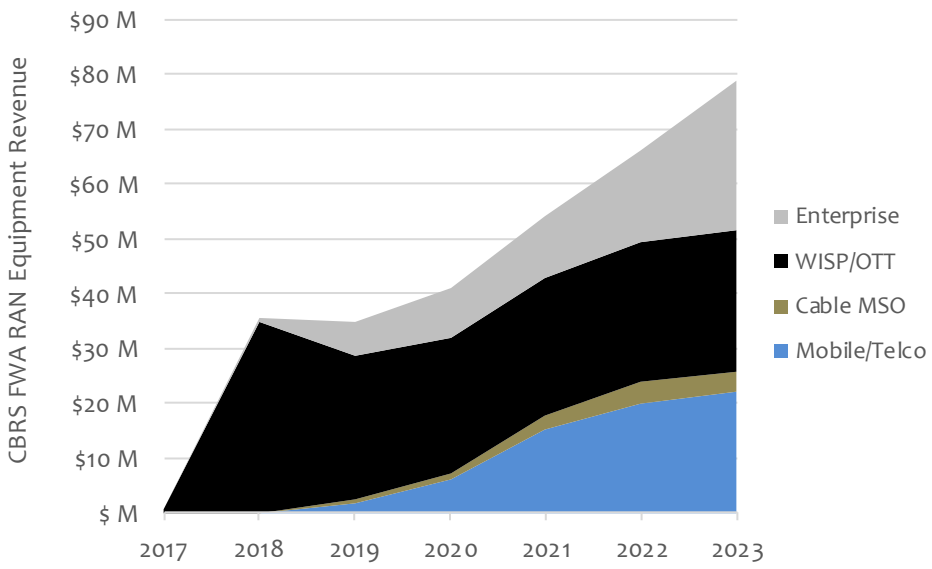
Customer Premise Equipment (CPE) will be deployed at the same time as the FWA infrastructure, as WISPs and others deploy or convert their sites with CBRS radio gears. As a result, the CPE forecast closely mirrors the infrastructure forecast as shown below.



Source: Mobile Experts

Chart 15: CBRS FWA CPE shipment forecast, by operator type, 2017-2023

In Fixed Wireless Access, the cumulative revenue associated with RAN infrastructure, including both FWA radios and the CPEs, will total about $70M in the first two years (2018 – 2019). The CBRS radio equipment revenue will gradually increase over time as certain mobile operators, and possibly the cable operators, expand into this market segment. While AT&T has formally announced its plan for fixed wireless deployment using CBRS, we currently expect very minimal participation by the cable operators for fixed wireless access. We believe that the primary motivation for both the mobile and cable operators is to increase mobile network capacity – not so much to enlarge their already expansive fixed broadband footprints.



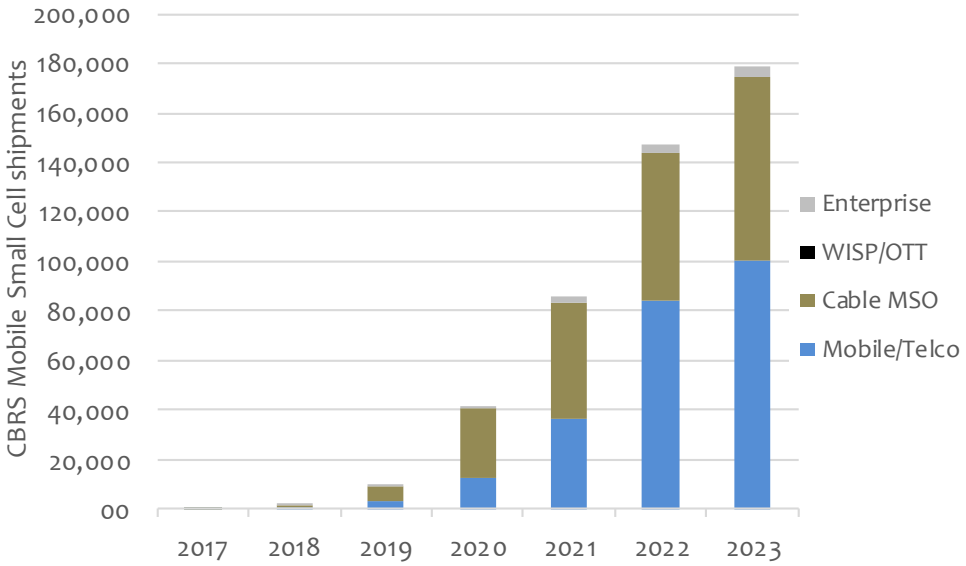
Source: Mobile Experts

Chart 16: CBRS FWA RAN equipment forecast, by operator type, 2017-2023

CBRS Mobile Access Forecast

With the updated CBRS rules, Mobile Experts expects the CBRS infrastructure deployment for mobile use by mobile and cable operators will dominate CBRS radio deployments in the outdoor setting. With a longer-term investment "protection" with relatively larger county-size coverage areas and 10-year term with renewability, major operators will be more inclined to spend on CBRS radio infrastructure knowing that the capital expenditure towards CBRS spectrum use will be protected from interference (most of the time when incumbent radar use is not present). We expect that for the mobile operators, handovers to adjacent cell sites and other control signaling will predominately leverage existing licensed carrier while leveraging the CBRS band for secondary carrier for Carrier Aggregation. For the cable operators, the outdoor mobile deployment of CBRS presents a new challenge in setting up a truly mobile network that can seamlessly handoff mobile traffic between host MVNO network, owned CBRS and Wi-Fi networks. Despite the challenges, the cable operators will be motivated to create facilities-based network capacity based on the CBRS spectrum to offset the MVNO "rent" costs.

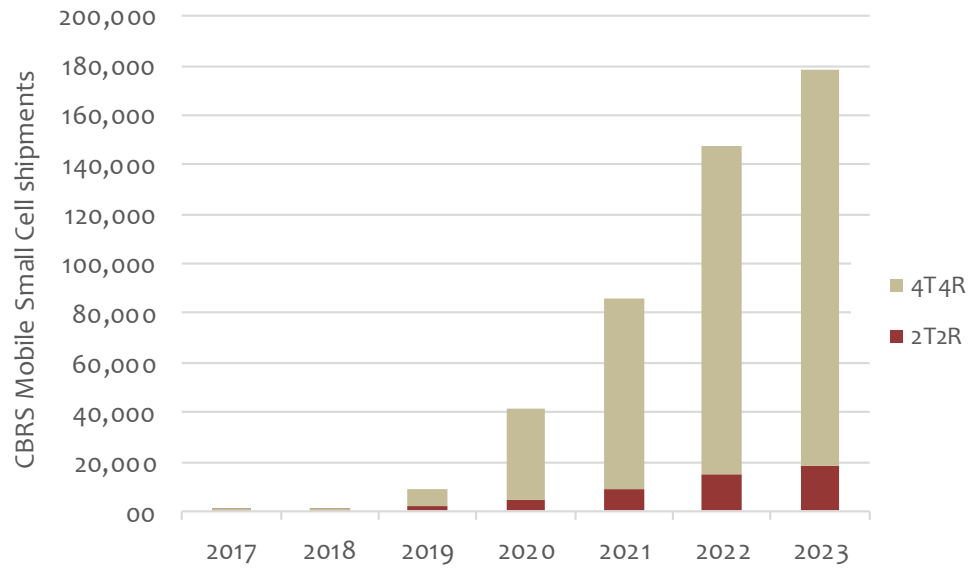
While we envision Private LTE deployments leveraging autonomous and portable IoT devices also to contribute to the mobile CBRS forecast, we currently expect this market opportunity to be small compared to general mobile use leveraging hundreds of millions of smartphones in the near term.



Source: Mobile Experts

Chart 17: CBRS Mobile AP shipment forecast, by operator type, 2017-2023

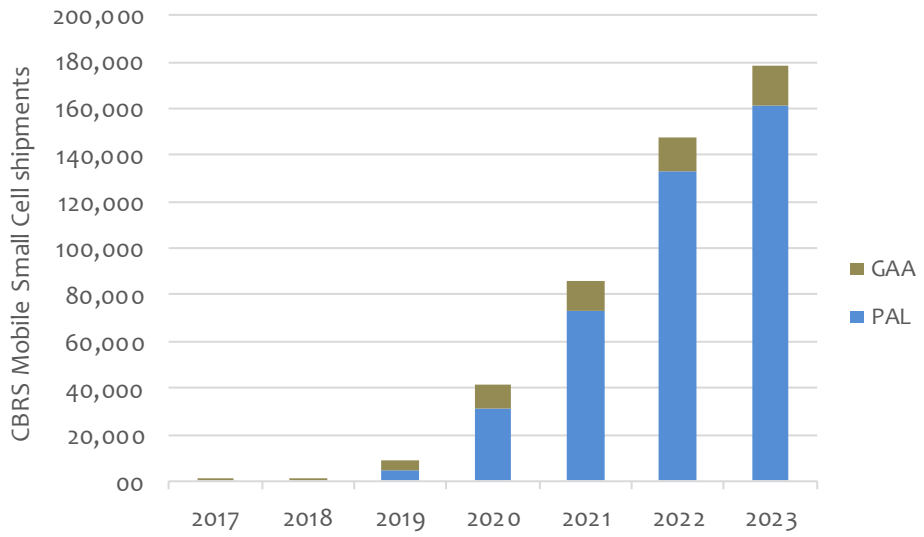
The MIMO configuration of mobile CBRS infrastructure will depend on the smartphones released in the marketplace. We expect most of these devices will support 4x4 MIMO longer term as operators upgrade their Macro layer to 4x4 to increase network capacity. Hence, almost all of the outdoor CBRS small cells are expected to also support 4x4 MIMO.



Source: Mobile Experts

Chart 18: CBRS Mobile AP shipment forecast, by MIMO order, 2017-2023

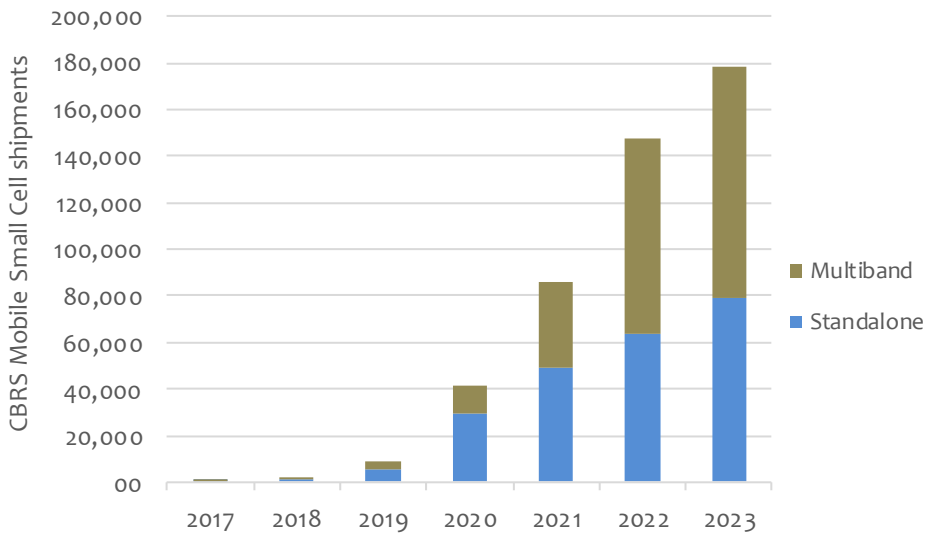
Because of the importance of service quality in challenging mobile application, a majority of CBRS radio infrastructure deployed by mobile and cable operators will operate on "licensed" PAL. While the initial deployments in 2019 will leverage GAA, major operator deployments will leverage PAL license, and some will opportunistically aggregate GAA spectrum to increase capacity and speed.



Source: Mobile Experts

Chart 19: CBRS Mobile AP shipment forecast, by GAA vs PAL, 2017-2023

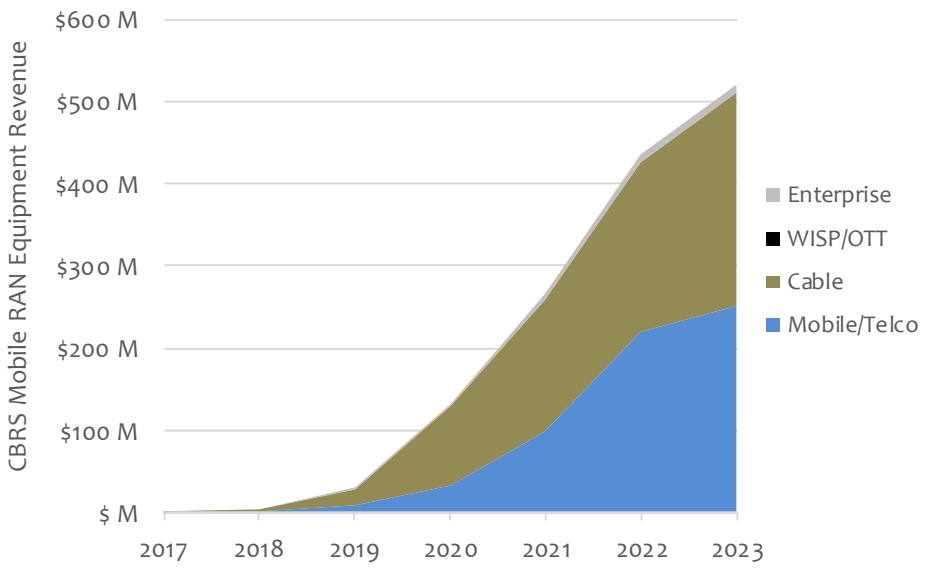
Over a long-term, more than half of the mobile CBRS deployment will be carried out by mobile operators, and a large part of the remainder will likely result from cable operator deployments expanding their mobile footprint. Because mobile operators will prefer multi-band small cells and cable operators are more likely to use single-band small cells, we anticipate a fairly evenly split market in the next few years with regard to band support. Over time, we expect mobile operators to more aggressively leverage the CBRS band as a part of multiband small cell deployment to increase network capacity.



Source: Mobile Experts

Chart 20: CBRS Mobile AP shipment forecast, multiband vs. standalone, 2017-2023

While revenue from mobile CBRS infrastructure equipment will not be hugely significant compared with the overall RAN market, this market opportunity can not be ignored. It will grow from zero to about $500M over the next five years, which is a significant leap for the small companies targeting the CBRS opportunity. There's no reason to believe that all market segments including cable MSOs, WISPs, and Private LTE deployments will be served by Ericsson and Nokia. A great deal of this revenue opportunity can be captured by aggressive players like Ruckus, Spidercloud/Corning, and other smaller suppliers.

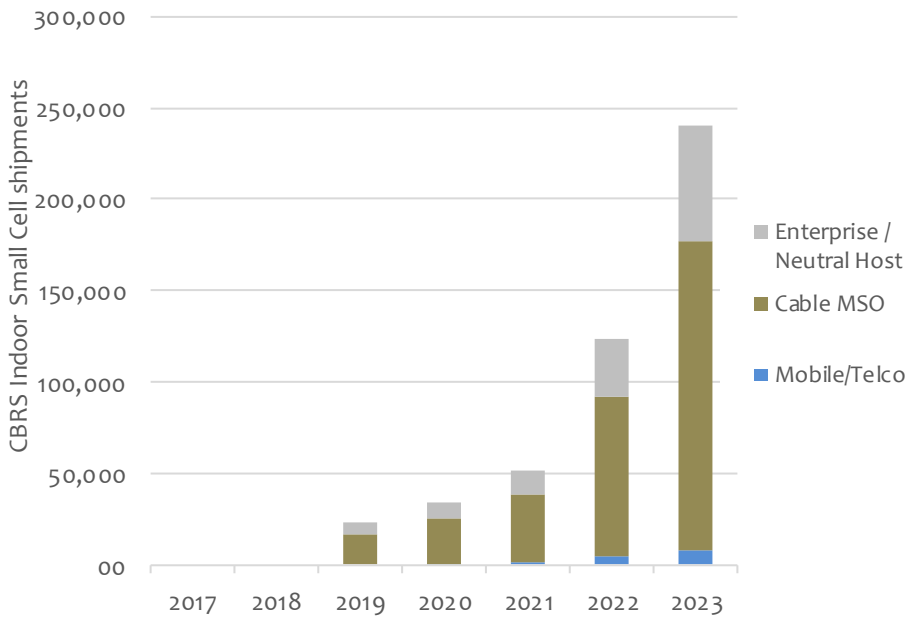


Source: Mobile Experts

Chart 21: CBRS Mobile AP revenue forecast, by operator type, 2017-2023

CBRS Indoor Access Forecast

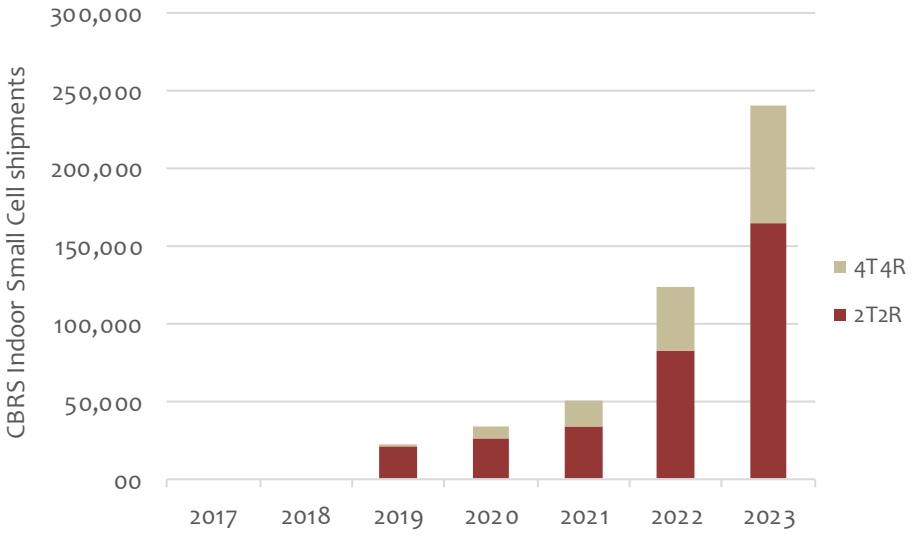
The indoor CBRS market will look different than fixed wireless or mobile outdoor markets. Indoor deployment will be fairly small from the mobile operators, but we expect significant growth from the cable operators looking to leverage their large fixed broadband footprint to expand mobile network coverage and capacity through their "inside-out" strategy whereby CBRS-enabled CPEs can be deployed to expand mobile coverage where possible. Moreover, we expect venues that want public wireless services, as well as industrial companies to also deploy indoor CBRS radios to create more "reliable" wireless network footprint that can support higher service quality assurance.



Source: Mobile Experts

Chart 22: CBRS Indoor AP shipment forecast, by operator type, 2017-2023

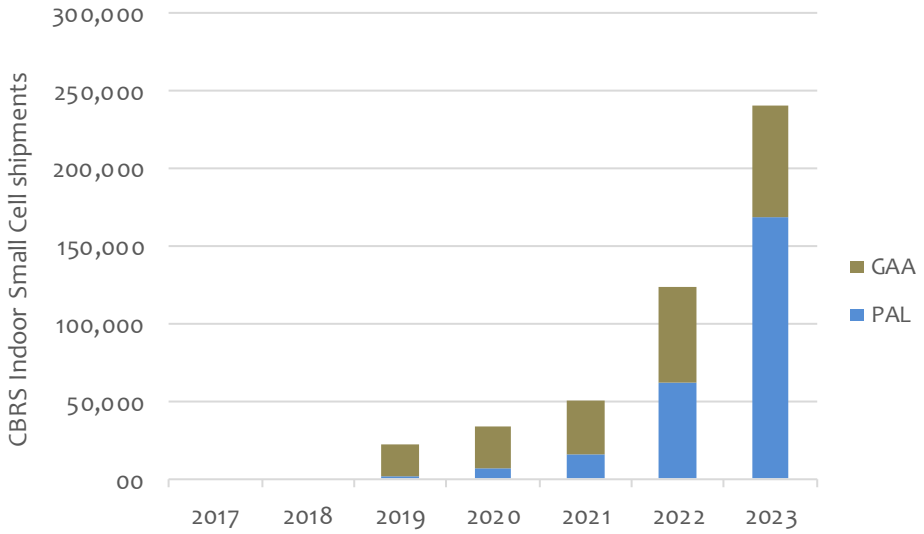
The indoor CBRS market will be closely tied to the availability of smartphones. A few early smartphones will use 2x2 MIMO technology but when the major smartphone platforms come out in the 2020-2021 timeframe, we expect them to overwhelmingly support 4x4 because the same RF paths will also support 5G.



Source: Mobile Experts

Chart 23: CBRS Indoor AP shipment forecast, by MIMO order, 2017-2023

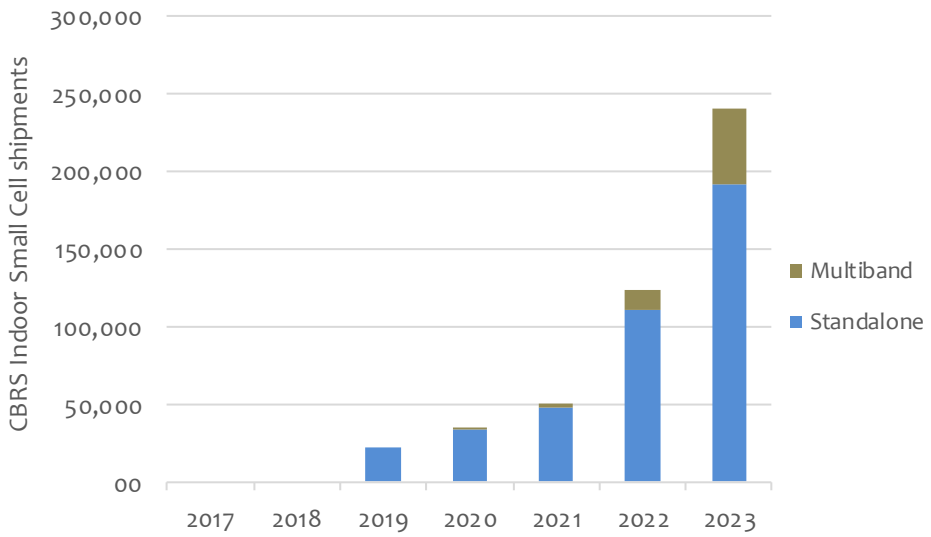
Most enterprises such as hotels or other large venues should be very comfortable with operating using a GAA license, as they have worked with Wi-Fi in the past and have no desire to get involved with PAL auctions. Large industrial Private LTE deployment could move toward PAL because these customers have a lot of money depending on the reliability of data. Deployment by operators is likely to be done under PAL licenses. With key assumption that cable operators will leverage their PAL licenses for indoor deployment, our forecast shows much significant share of PAL use in the later years of our forecast period.



Source: Mobile Experts

Chart 24: CBRS Indoor AP shipment forecast, by GAA vs PAL, 2017-2023

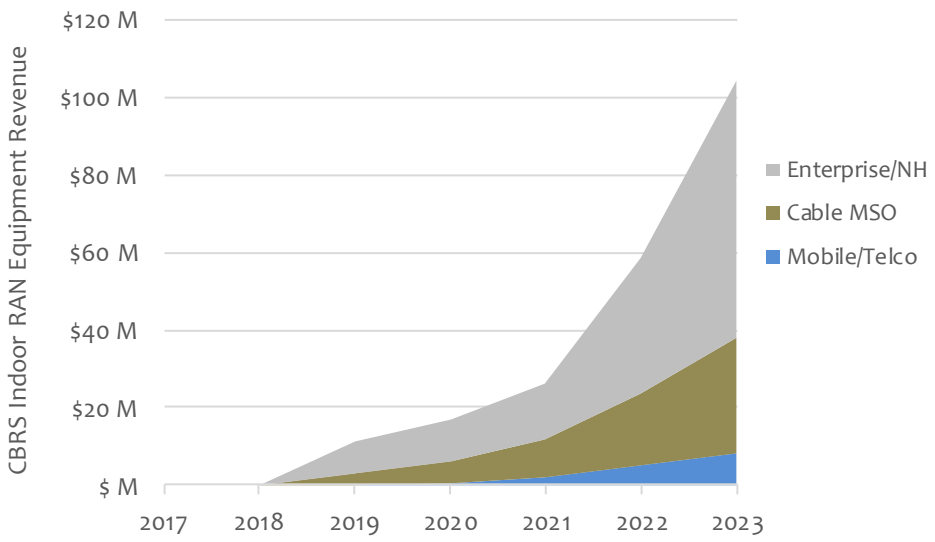
All Private LTE deployments should be single-band in nature, and even the deployments that are funded by operators are likely to use single-band CBRS in the indoor market. Cable operators certainly will use stand-alone CBRS small cells, and even mobile operators could use stand-alone CBRS in some cases.



Source: Mobile Experts

Chart 25: CBRS Indoor AP shipment forecast, multi-band vs standalone, 2017-2023

Revenue for indoor CBRS small cells will not be huge, because the majority of indoor units deployed by the cable operators will be inexpensive CPE units with low-power CBRS radios. While the unit shipment is large, the revenue contribution will be somewhat muted. Other CBRS indoor units deployed by enterprise and neutral host network operators for Private LTE and general indoor wireless use will provide higher revenue contribution as they will generally be more expensive higher power units. In 2023, Mobile Experts forecasts the indoor CBRS segment to reach over $100M in radio equipment revenue.



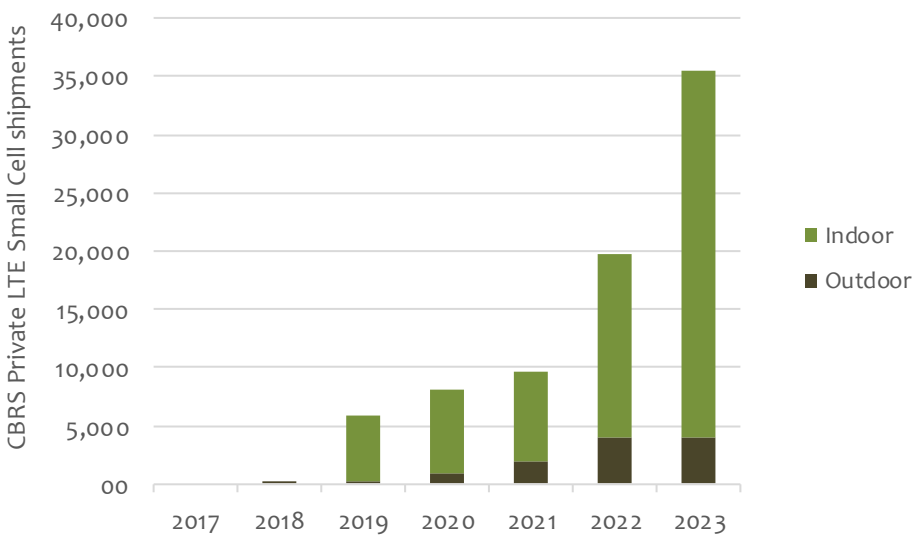
Source: Mobile Experts

Chart 26: CBRS Indoor AP revenue forecast, by operator type, 2017-2023

Private LTE Forecast

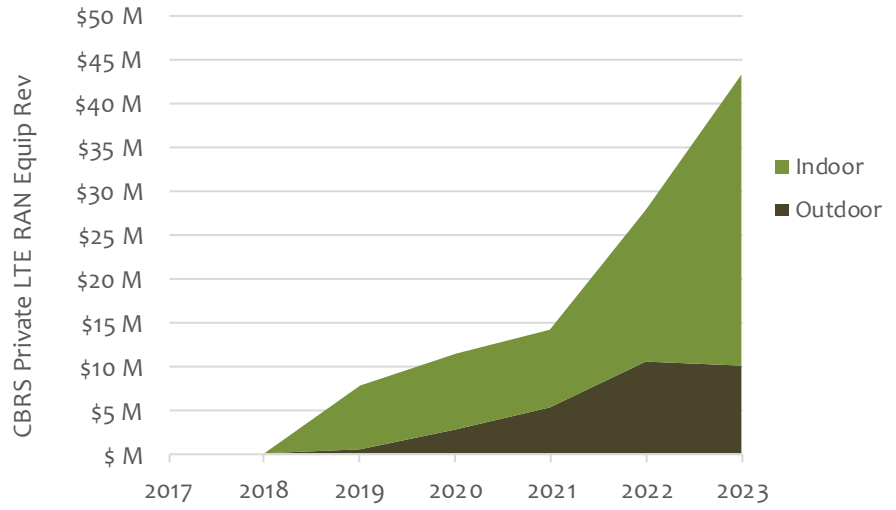
In the previous CBRS Indoor market segment, we combined Enterprise deployment with Neutral Hosts, because many enterprises will use Neutral Hosts in order to deploy their Private LTE networks. In fact it may be difficult to distinguish between Private LTE and a Neutral Host CBRS network, as these systems could be set up for easy authentication and use by any smartphone that comes through.

To help in clarifying the market drivers behind deployment, we've isolated the deployments that are intended for truly private LTE use, for example in port operations, asset tracking, industrial IoT, or corporate smartphone access. The shipments and revenue shown in this segment should not be added to the Outdoor and Indoor CBRS market estimates, because Private LTE is already included in those numbers.



Source: Mobile Experts

Chart 27: CBRS Private LTE AP shipment forecast, indoor and outdoor, 2017-2023



Source: Mobile Experts

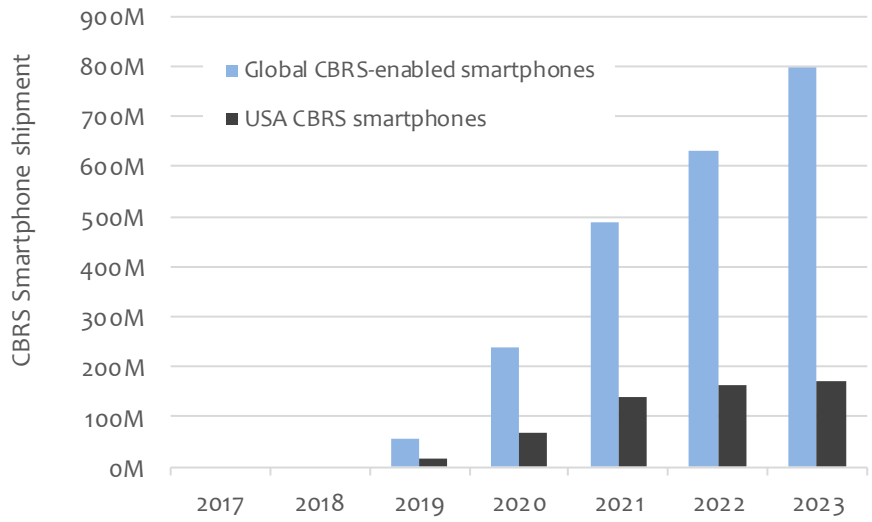
Chart 28: CBRS Private LTE AP revenue forecast, indoor and outdoor, 2017-2023

CBRS End Devices Forecast

The smartphone market has not earnestly engaged in product development for CBRS like the infrastructure market. Frankly, the availability of smartphones and other CBRS end device terminals is largely dependent on infrastructure investment. From device

manufacturers' viewpoint, if there is a clear market and the opportunity is big enough, they have always been willing and able to bring products to market. Major "flagship" smartphone devices are not likely to include CBRS until 5G services in the 3.5 GHz band are also introduced in China, during late 2019 to 2020. We expect other smaller smartphone platforms to move more quickly in supporting the CBRS band 48.

For Private LTE networks, corporate employees are likely to get dual SIM smartphones, so that they can enjoy access through the corporate LTE coverage indoors while using their normal LTE operator everywhere else. With the dual-SIM support in the latest Apple smartphones including iPhone XS and XR, it appears that the dual-SIM support may become a mainstream feature allowing multi-network operation for Private LTE and MVNO offload use.

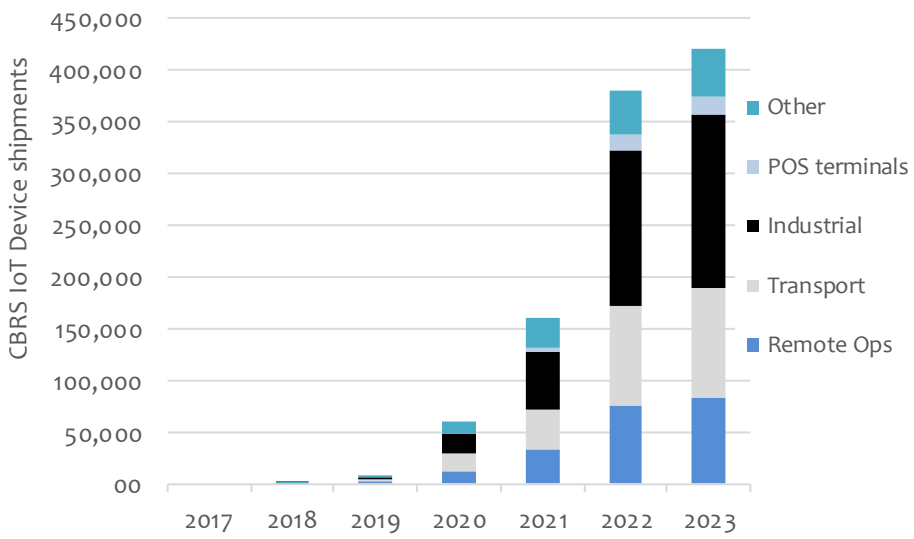


Source: Mobile Experts

Chart 29: CBRS-Enabled Smartphone forecast, 2017-2023

IoT devices are a bit more tricky as multiple different market segments will drive the use of Private LTE. One of the biggest drivers today in industrial and transportation applications is the use of cameras to stream video. This can be for security purposes, or for safety in heavy industrial operations with cranes and robots moving around.

It's early days, so our current forecast for Private LTE/IoT market segment splits the devices into mining, transportation, industrial, POS, and other applications somewhat evenly. (Our initial forecast will be refined further as we dive deeper into the Private LTE market study coming in early 2019.)



Source: Mobile Experts

Chart 30: CBRS Private LTE IoT Device forecast, by application, 2017-2023

6 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ad: An IEEE standard for 60 GHz short-range communications.

802.11ah: An IEEE standard for unlicensed communications below 1 GHz.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

ACLR: Adjacent Channel Leakage Power Ratio (amount of power leaking into adjacent channels).

AES: Advanced Encryption Standard.

Android: Google's mobile device operating system.

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BSC: Base Station Controller

BTS: Base Transceiver Station

Bits/Hz/sec: Digital bits transmitted per Hertz of bandwidth per second

CA: Carrier Aggregation

CAF: Connect America Fund

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EMEA: Europe, Middle East and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ePDG: Evolved Packet Data Gateway.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

GSM: Global System for Mobile communications, a 2G radio interface

GTP: GPRS Tunneling Protocol

GW: Gateway (normally referring to a femto gateway)

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

HEW: High-Efficiency Wireless (now renamed 802.11ax)

HLR: Home Location Register.

HSPA: High-Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IKEv2: Internet Key Exchange (version 2)

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

LWA: LTE/Wi-Fi Aggregation (use of LTE signals on both licensed control channels and licensed data channels, and Wi-Fi signals on unlicensed data channels).

MAC: Media Access Control layer

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

NHN: Neutral Host Network

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

PAMid: PA Module Integrated Duplexer (RF frontend module containing PA, SAW duplexer, switch, transmitter low-pass filter, and receiver SAW filter)

Passpoint: A certification stamp for Hotspot 2.0 equipment, administered by Wi-Fi Alliance

PC: Personal Computer

PEA: Partial Economic Area

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SNR: Signal-to-Noise Ratio

SSID: Service Set Identification

TD-LTE: Time Domain-based Long Term Evolution

UE: User Equipment

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

7 METHODOLOGY

To create estimates and forecasts for the CBRS market, Mobile Experts relied on direct input from more than 30 industry sources, with many different mobile, cable, and ISP operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts has also spoken with more than 40 other companies in related business areas for Carrier Wi-Fi, LTE-U, and LTE business areas—providing some valuable cost estimates and background data for potential CBRS growth.

Mobile Experts built a "top-down" forecast based on direct input from mobile operators, cable operators, neutral host companies, and wireless Internet service providers (WISPs). . Then, Mobile Experts built a "bottom-up" forecast through discussions with OEMs, software developers, and semiconductor suppliers in the supply chain. For this early market, financial disclosures were not useful, so we relied on our cost analysis to make predictions about the likely course of technology choices for each business model.

Private LTE deployment was considered as a part of the overall CBRS market. Some Private LTE systems will be deployed by Neutral Host companies, then owned by the Enterprise. We consider these to be Private LTE networks. Other systems (in public buildings such as hotels or stadiums) will be owned by the Neutral Host, with coordination with Verizon/AT&T/T-Mobile to support multi-operator access. These are not included in the Private LTE totals.

For handset and IoT device forecasts, Mobile Experts interviewed multiple suppliers in the handset market to determine the maturity of RF filter technology and the software to support the unique restrictions of CBRS operation. Our direct interviews resulted in the delayed timing of the forecast reflected throughout this report.